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Magnetohydrodynamics (MHD) Engineering Test Facility (ETF) 200 MWe Power Plant

Conceptual Design Engineering Report (CDER) Supplement

Magnet System Special Investigations

Massachusetts Institute of Technology
Francis Bitter National Magnet Laboratory

September 1981

Prepared for
National Aeronautics and Space Administration
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MHD-ETF
CONCEPTUAL DESIGN
ENGINEERING REPORT

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1.0 INTRODUCTION

This report supplement summarizes the results of two special investigations made by Massachusetts Institute of Technology, Francis Bitter National Laboratory (FBNML) as a part of the overall conceptual design study of the MHD/ETF for which NASA LeRC has management responsibility. The two investigations, included in FBNML's Phase II effort by letter agreement[9] under NASA LeRC Grant NAG-3-100, are the 4 Tesla Magnet Alternate Design Study (Task 1 of reference letter), and the 6 Tesla Magnet Manufacturability Study (Task 2 of reference letter).

These investigations supplement the 6 T magnet system conceptual design work performed by FBNML and reported in Section SDD503 of the ETF Conceptual Design Engineering Report (CDER).[1]

2.0 4 TESLA MAGNET ALTERNATE DESIGN

A 4 tesla superconducting magnet system conceptual design was prepared by FBNML for NASA LeRC's use in their investigation of an alternate (supersonic) power train for the ETF.

Design work was initiated in August, 1981, upon receipt of requirements from NASA LeRC. Specified were a peak field of 4 tesla with a field profile shape, active length, and warm bore dimensions the same as those of the 6 T magnet design prepared by FBNML for NASA LeRC and described in the ETF Conceptual Design Engineering Report (CDER), System Design Description SDD503. (The 6 T magnet is intended for use in a subsonic power train.)

The 4 T magnet system design, described below, derived by scaling techniques from the 6 T magnet design, is intended to establish approximate system characteristics only, and is not optimized. Should NASA LeRC investigations and/or other studies show the alternate (supersonic) power train to be sufficiently attractive to warrant further examination, the 4 T magnet system design should be investigated in greater depth.

2.1 DESIGN SUMMARY

The major characteristics and estimated cost of the 4 T magnet system design compared to the original 6 T design are listed in Table 2.1

TABLE 2.1

Major Characteristics and Estimated Costs

4 T and 6 T Magnet Systems

	4 T Design (Scaled)	6 T Design (SDD503)
Peak on-axis field	4 T	6 T
Active Length	12.1 m (39' 8")	12.1 m (39' 8")

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TABLE 2.1 (continued)

	4 T Design (Scaled)	6 T Design (SDD503)
Field at start of active length	2.67 T	4 T
Field at end of active length	2.33 T	3.5 T
Aperture* at start of active len.	55" x 71"	55" x 71"
Aperture* at end of active length	81" x 106"	81" x 106"
Magnet overall length	54' 4"	54' 4"
Magnet outside diameter	26' 0"	27' 6"
Magnet weight	1.25×10^6 lbs	2×10^6 lbs
Magnet system estimated cost**	$\$47 \times 10^6$	$\$58 \times 10^6$

* aperture dimensions are inside water-cooled warm bore liner

** cost estimates are based on conceptual design as it existed prior to the manufacturability study described in Section 3.0 of this report

Outline dimensions of the 4 T magnet are shown in Fig. 2.1, the field profile is shown in Fig. 2.2 and fringe magnetic field zone boundaries (personnel exclusion zones) are shown in Fig. 2.3.

The design characteristics of the magnet system are listed in Table 2.2 and the utility requirements in Table 2.3.

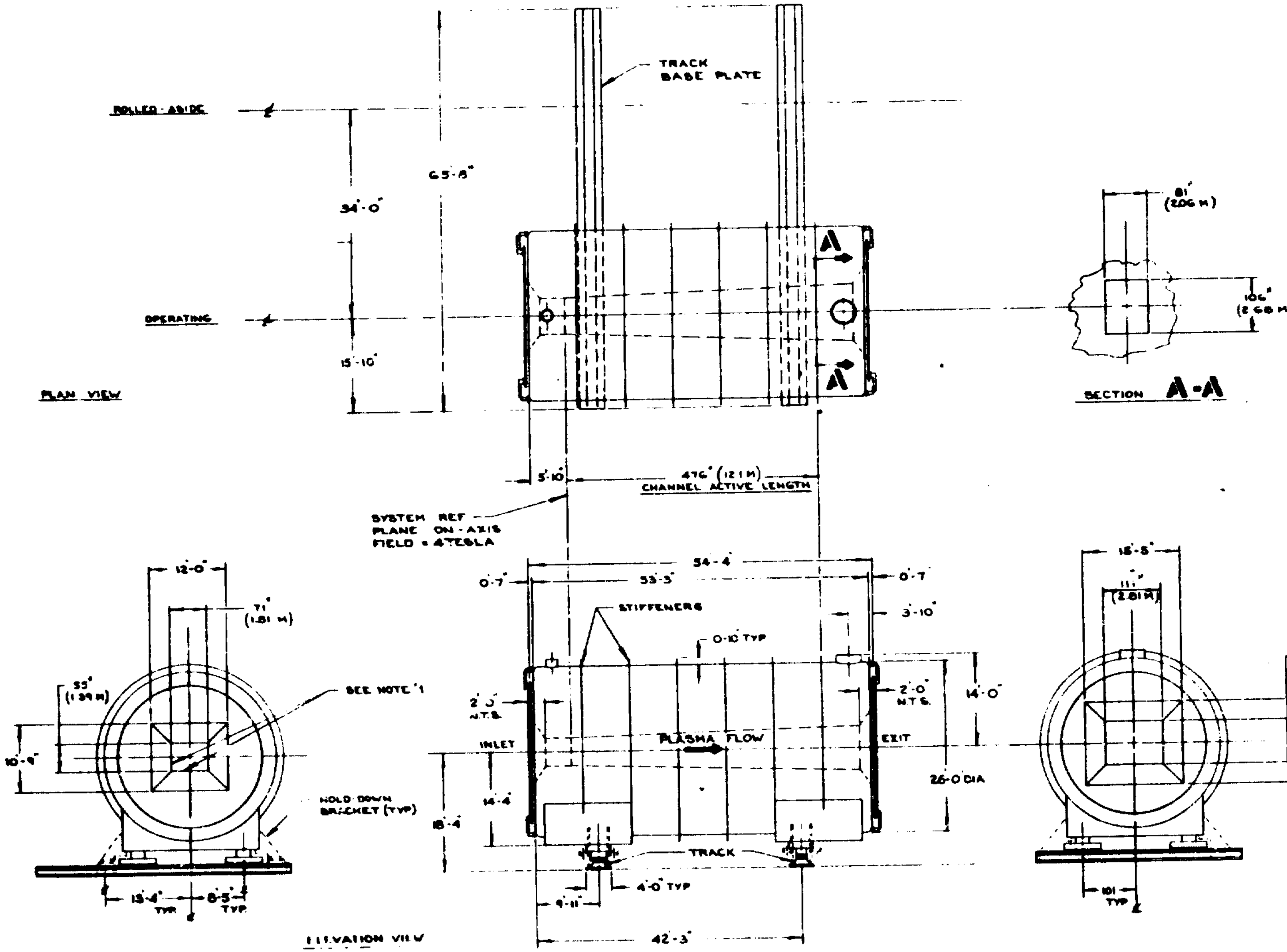
2.2 DESIGN DESCRIPTION

Consistent with requirements given by NASA LeRC, the 4 T magnet retains the same warm bore aperture dimensions, the same shape of field profile and the same overall length as the 6 T magnet from which it has been scaled.

Also, it retains the same type of winding (60° rectangular saddle), the same type of conductor (circular cable), substantially the same design current (∿ 25,000 A) and similar designs of substructure, superstructure and cryostat.

In scaling down to the 4 T field strength, ampere-turns and structural requirements are substantially reduced, so the magnet becomes smaller in diameter, lighter in weight and less expensive, both in material, fabrication and assembly cost.

In the following paragraphs, the design of components is described and scaling of the components of the magnet and of the accessory systems is discussed.



NOTE:
1. BORE CROSS-SECTION DIMENSIONS ARE INSIDE WARM BORE LINER
2. DIMENSIONS ARE IN FEET EXCEPT WHERE OTHERWISE NOTED
3. HOLD-DOWN BRACKETS ARE DESIGNED TO HOLD MAGNET FIRMLY IN PLACE IN "OPERATING" POSITION. THEY WILL BE DISENGAGED WHEN MAGNET IS TO BE ROLLED ASIDE

SCALE

0 5 10 15 20 25

FEET

Figure 2.1

4 T Magnet Outline

* F1113

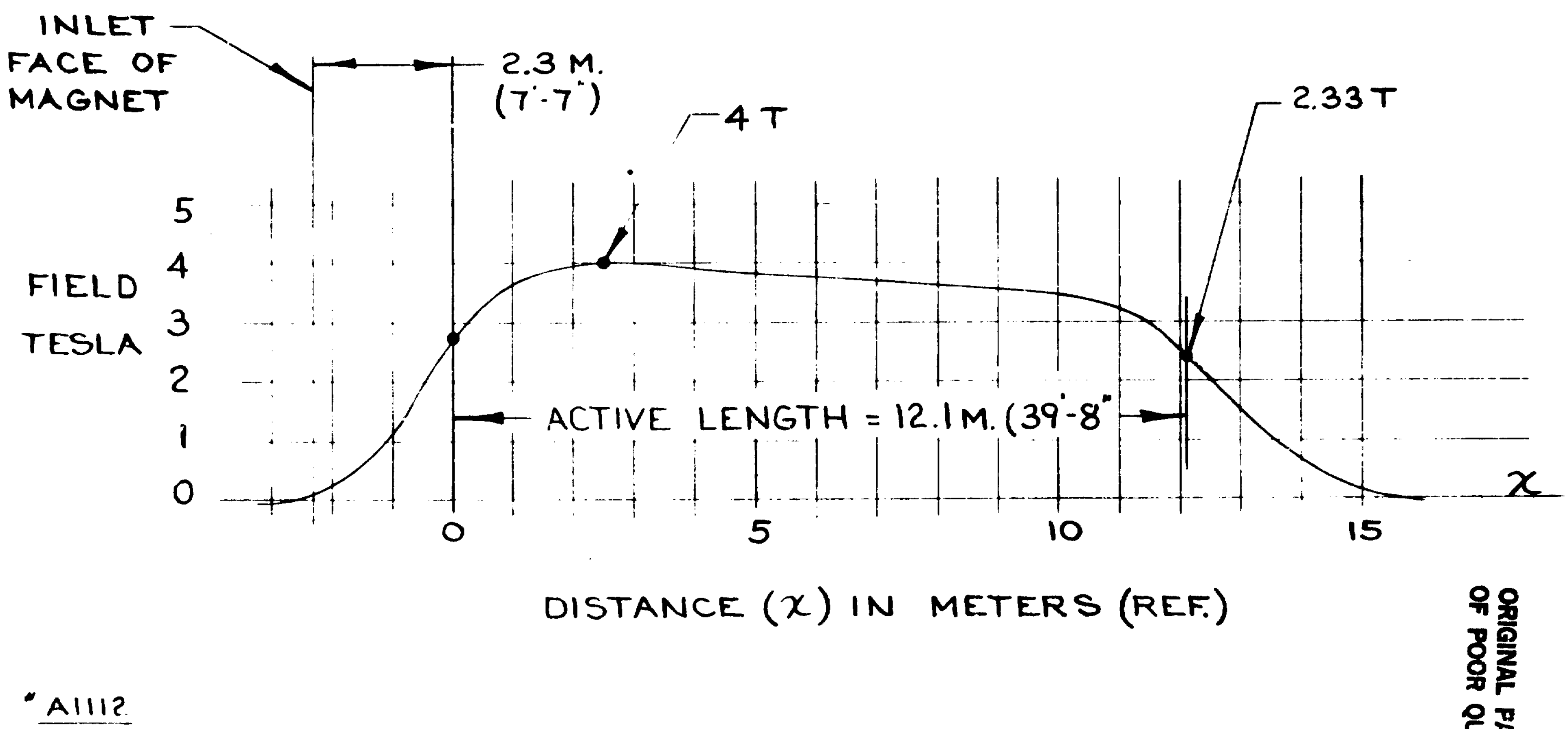
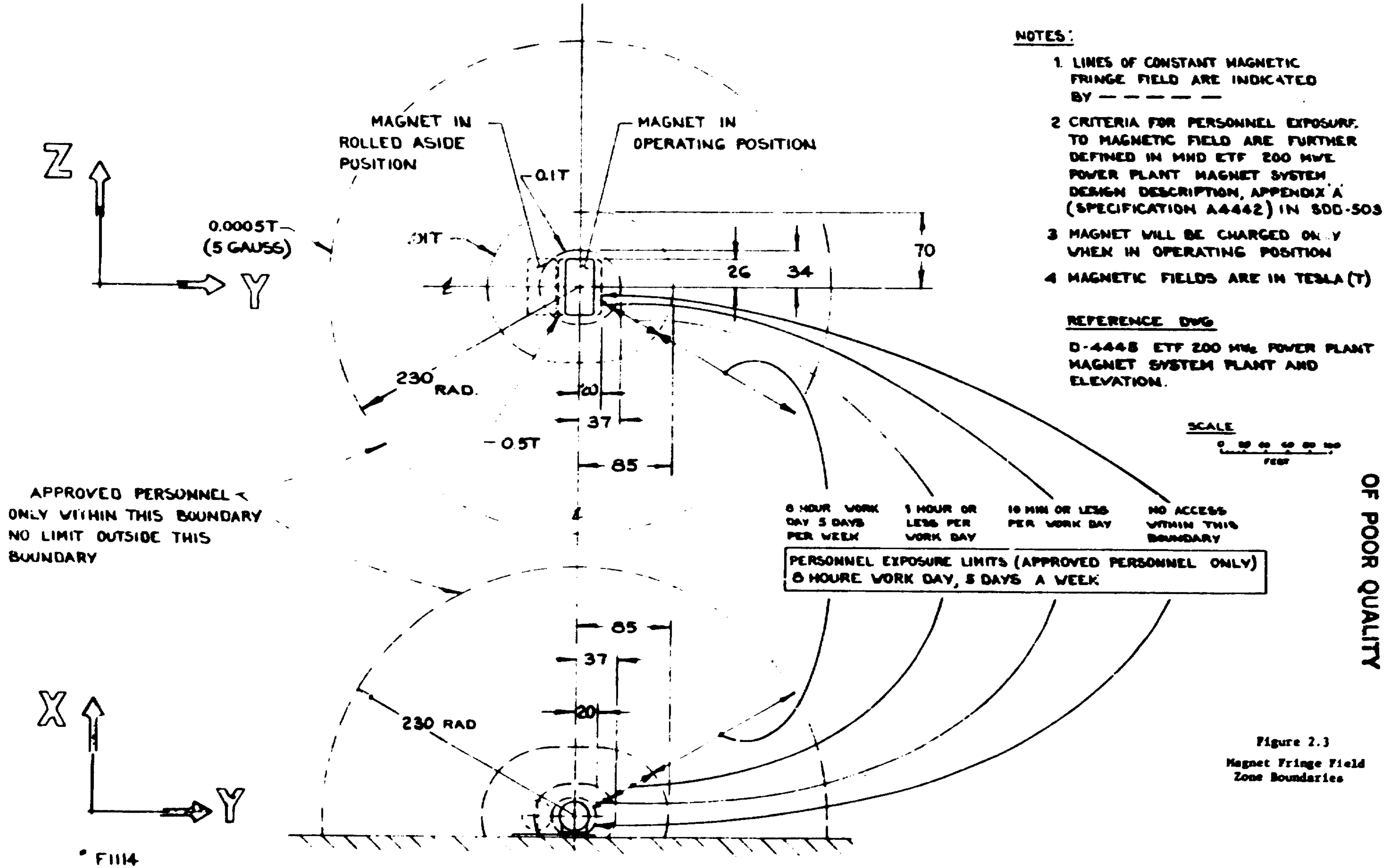


Figure 2.2
4 T Magnet Field Profile



NOTES:

1. LINES OF CONSTANT MAGNETIC FRINGE FIELD ARE INDICATED BY — — — — —
2. CRITERIA FOR PERSONNEL EXPOSURE TO MAGNETIC FIELD ARE FURTHER DEFINED IN MHD ETF 200 MWE POWER PLANT MAGNET SYSTEM DESIGN DESCRIPTION, APPENDIX A (SPECIFICATION A4442) IN SDD-503
3. MAGNET WILL BE CHARGED ONLY WHEN IN OPERATING POSITION
4. MAGNETIC FIELDS ARE IN TESLA (T)

REFERENCE DWG

D-4448 ETF 200 MWe POWER PLANT MAGNET SYSTEM PLANT AND ELEVATION.

Figure 2.3
Magnet Fringe Field
Zone Boundaries

TABLE 2.2 Sheet 1 of 2

4 T MAGNET SYSTEM
MAGNET DESIGN CHARACTERISTICS

Magnetic Field:	
Peak on-axis field	4 T
Active field length	12.1 m (39' 8")
Field at start of active length, B_{IN}	2.67 T
Field at end of active length, B_{EX}	2.33 T
Peak field in winding	5.3 T
Dimensions:	
Aperture, warm bore inlet*	55" x 71"
Aperture, start of active length*	55" x 71"
Aperture, end of active length*	81" x 106"
Aperture, warm bore exit*	85" x 111"
Length of warm bore	49' 9"
Distance, bore inlet to start of active length	3' 6"
Vacuum vessel overall length, including water-cooled warm bore liner	54' 4"
Vacuum vessel outside diameter	26' 0"
Winding Characteristics:	
Design current	25,000 A
Winding current density	1.4×10^7 A/m^2
LHe to conductor ratio (volume)	1.1
Ampere turns	18×10^6
Ampere meters	7×10^8
Inductance	4.2 henries
Stored energy	1300 MJ
Winding Dimensions:	
Depth (build), winding cross-section	25"
Height, winding cross-section, one quadrant	40.7"
Gap (distance from winding to bore surface inside warm bore liner)	16.7"

*Inside water-cooled warm bore liner

TABLE 2.2 Sheet 2 of 2

Conductor:	
Type	Cable
S.C. material	NbTi
Overall diameter	1.0"
Strand diameter	0.046"
Cu/SC in high field regions	12
Total length conductor	93,000'
Weights:	
Conductor	149,000 lbs.
Insulation	(included in substructure)
Substructure	132,000 lbs.
Superstructure and coil containment vessels	560,000 lbs.
Total cold mass	841,000 lbs.
Thermal radiation shield, cold mass supports, etc.	60,000 lbs.
Vacuum vessel and mounting feet	329,000 lbs.
Miscellaneous	20,000 lbs.
Total Magnet Weight	1,250,000 lbs.
Cryogenic Data:	
Operating temperature at winding	4.5 K
Heat leak to LHe region	170 watts
Liquid helium for lead cooling	75 ℓ/hr.

TABLE 2.3

4 T MAGNET SYSTEM

UTILITY REQUIREMENTS

Electric Power (60 Hz)			
Power supply - Maximum charging	4160 V	1250 KW	3ϕ
- Steady state of operation	4160 V	300 KW	3ϕ
Refrigerator/liquefier	220 V	10 KW	1ϕ
Refrigerator compressors	440 V	500 KW*	3ϕ
Utility vacuum pump	220 V	15 KW	3ϕ
Diffusion pumps, main vacuum (2)	440 V	24 KW	3ϕ
Fore pumps, main vacuum (2)	440 V	20 KW	3ϕ
Warm-up heat exchanger	440 V	TBD	3ϕ
Hydraulic pump package	440 V	20 KW	3ϕ
Cooling Water (80° F max., 50 psig except 100 psig for warm bore liner)			
Power supply (rectifiers; diodes)		35 GPM	
Discharge resistors		50 GPM	
Refrigerator compressors		150 GPM	
Refrigerator/liquefier		3 GPM	
Diffusion pumps, main vacuum (2)		5 GPM	
Fore pumps, main vacuum (2)		5 GPM	
Warm bore liner - Steady-state		40 GPM	
- Emergency		200 GPM	
Water-cooled power bus		30 GPM	
Liquid Nitrogen (30 psig)			
Cool-down heat exchanger (during cool-down only)		TBD	
Refrigerator pre-cooling (steady state)		150 ℓ/hr.**	
Magnet radiation shield, transfer lines, etc.(steady-state)		60 ℓ/hr.**	
Compressed Air (90 psig)			
Refrigerator and vacuum system controls		25 SCFM	

* Nominal running power with power factor = 0.9. Starting requires 3 x running power.

** The refrigerator, thermal shield and transfer line LN_2 requirements totaling 210 ℓ/hr (steady state) will be supplied from facility air separation unit.

2.2.1 Windings and Substructure

The windings for the 4 T magnet are similar in configuration and substantially the same in overall length and width of straight section as those of the 6 T design. The depth (build) of the winding bundles is reduced to about 2/3, so that the design field of 4 T is produced with about the same overall current density in the windings as that of the 6 T design. The reduced depth results in a reduction in the outside envelope dimensions of the winding end turns.

The windings of the 4 T magnet are more conservative than those of the 6 T design, because more copper is provided relative to the current carried, and the magnetoresistance of the copper is lower because of the lower field in the winding. The cryostatic stability margin is greater than in the 6 T design.

The cable conductor is supported in a substructure of molded glass-reinforced plastic similar in design to that of the 6 T magnet.

The dimensions of the winding envelope for the 4 T magnet are shown in Fig. 2.4.

2.2.2 Conductor

The conductor is similar in material, configuration and design current to that of the 6 T magnet, i.e, NbTi/copper cable 1 inch in diameter with 259 strands, part of which are NbTi/copper composite wires (monoliths) and part of which are copper wires. The conductor is in two grades, as in the 6 T magnet, to reduce the total amount of NbTi required.

The maximum field to which the conductor is exposed in the 4 T magnet is lower, and therefore there are fewer strands of composite wire in the conductor and more of copper wire than in the corresponding conductor for the 6 T magnet.

Approximate conductor characteristics are listed in Table 2.4.

TABLE 2.4

4 T Magnet Conductor (Cable) Characteristics

	Grade A	Grade B
Design current (A)	25,000	25,000
Magnetic field (T)	5.3	3.5
NbTi current density (A/m^2)	11.6×10^4	16.2×10^4
Total number of strands	259	259
Copper strands	79	115
Composite strands	180	144
Strand diameter (in)	0.046	0.046

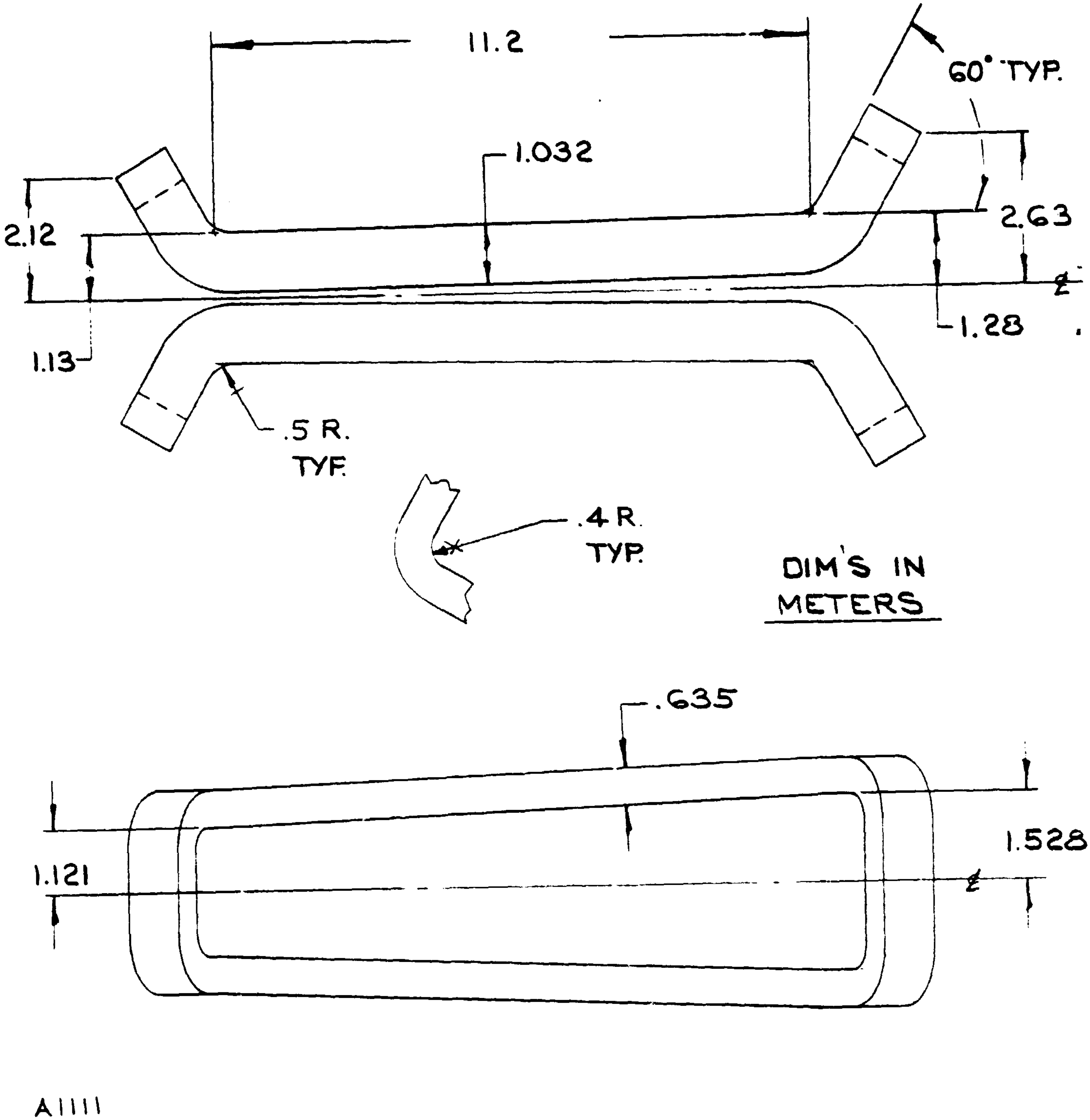


Figure 2.4
4 T Magnet Winding Envelope

TABLE 2.4 (continued)

	Grade A	Grade B
Cu/Sc ratios		
Composite strands	8	8
Overall cable	12	15
Finished length required (ft.)	42,500	50,500
Weight/length, average (lbs/ft)	1.07	1.07

To provide a conservative performance margin, the conductor design current is set at 85% of the specified maximum current capability (critical current) for the cable at the operating temperature of 4.5 K, the same as in the 6 T design.

2.2.3 Winding Containment Vessels

The two winding halves are enclosed in winding containment vessels of the same design and material as those of the 6 T magnet. The wall thickness of the containment vessels is reduced to 1½ inches in the straight section and 2 inches in the end-turn regions(compared to 2 inches and 3 inches, respectively, in the 6 T design). The wall thickness of the vessels is determined in part by their function in containing a portion of the magnetic forces on the windings. The reduction in wall thickness is therefore justified because of the reduction of magnetic forces and pressures (by a factor of roughly 0.45). Reduction of thickness by the full 0.45 factor is not practical, however, because of deflection considerations.

2.2.4 Main Force Containment Structure

The main force containment structure, consisting of welded stainless steel I-beams, threaded tie-rods, nuts and spherical washers, is similar to that of the 6 T magnet except that beam and rod cross-section areas are reduced by a factor of approximately 0.45, in view of the reduced magnetic forces.

2.2.5 Thermal Radiation Shield

The thermal shield, of the same design as the 6 T magnet shield, is reduced in outside diameter by about 0.95 because of the slightly smaller outside dimensions of winding and containment vessels. The overall length of shield and the size of the bore portion of the shield are the same as for the 6 T magnet.

2.2.6 Low Heat Leak Supports

The supports are the same design as for the 6 T magnet but are reduced in cross-section area roughly in proportion to the cold mass weight reduction (reduction in weight of winding, containment vessels and main structure).

The smaller cross-section results in a slight reduction in heat leakage into the cold mass, but since this is a small fraction of total refrigerator load, it is not considered worthwhile to reduce refrigerator size.

2.2.7 Vacuum Jacket and Warm Bore

The vacuum jacket and warm bore are of the same design as those of the 6 T magnet. The outside diameter is reduced by about 0.95, consistent with the more compact winding. Overall length and warm bore size remain identical to those of the 6 T design. The base portion of the vacuum jacket, including support pads, is slightly lighter in construction due to the lower weight of the cold mass.

2.2.8 Water-Cooled Warm Bore Liner

The water-cooled warm bore liner is identical to that of the 6 T magnet.

2.2.9 Vapor Cooled Electrical Leads, Internal Instrumentation, etc.

These items also are identical to those of the 6 T magnet.

2.2.10 Roll-Aside System

The roll-aside system is the same design as that of the 6 T magnet but is lighter in weight because of the lower total weight of the 4 T magnet assembly.

2.2.11 Cryogenic Support Equipment

The equipment is identical to that of the 6 T magnet system except for the gaseous helium storage tanks and the cooldown and warm up heat exchangers.

The gaseous helium storage tanks of the cryogenic support system, if sized for the 6 T magnet, would have some excess capacity when used with the 4 T magnet, because the latter has about 30% lower liquid helium inventory. Therefore, slightly smaller storage tanks are provided.

The size of the cooldown and warmup heat exchangers are reduced by the ratio of magnet cold mass weights.

2.2.12 Vacuum Pumping Equipment; Protection/Control Equipment and Instrumentation

These items are similar to those of the 6 T magnet system.

2.2.13 Power Supply and Discharge Equipment

This equipment is similar in design to that of the 6 T magnet equipment but is scaled down by approximately the ratio of the estimated inductances of the magnets (ratio = $\frac{4.15}{9.7}$).

The characteristics of the power supply and discharge system for the 4 T magnet are listed in Table 2.5.

It should be noted that the maximum terminal voltage for a three minute emergency discharge is now a relatively conservative 4.3 kV as compared to 10 kV for the 6 T magnet.

2.3 COST ESTIMATE, 4 T MAGNET SYSTEM

A rough budgetary cost estimate for the 4 T magnet system is presented in Table 2.6.

TABLE 2.5

4 T MAGNET SYSTEM

POWER SUPPLY AND DISCHARGE

SYSTEM CHARACTERISTICS

Rated current	25,000 A
Rated voltage	45 V
Current regulation	2%
Minimum charge time	
0 A to 25,000 A (L = 4.2 henries)	45 min.
Minimum discharge time	
25,000 A to 0 A, normal discharge	45 min.
Minimum discharge time, emergency,	
25,000 A to 0 A	3 min.
Maximum discharge voltage	4.3 kV
Output power	
Maximum charging	1125 kW
Steady state operation	300 kW

TABLE 2.6

SUMMARY COST ESTIMATE [1,2]

ETF 4 T MAGNET SYSTEM

CONCEPTUAL DESIGN

ACCOUNT DESCRIPTION	QUANTITY	MATERIAL COST MJR COMP	MATERIAL COST BOA	INST. COST	INDIR COST	CONTIN	TOTAL COST
MAGNET SYSTEM	1	26,299	60	6,180	618	9,410	42,567
ENGINEERING SERVICES (FIELD)	-	-	-	2,653	-	530	3,183
OTHER COSTS	-	-	-	900	-	180	1,080
TOTAL ESTIMATED COSTS	-	26,299	60	9,733	618	10,120	46,830

[1] Costs are K$, mid 1981.

[2] Does not include foundations.

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3.0 6 TESLA MAGNET MANUFACTURABILITY STUDY

A manufacturability study and revised cost estimate were made by FBNML for the 6 T superconducting magnet system included in the MHD-ETF 200 MWe Power Plant described in the Conceptual Design Engineering Report (CDER)[1].

The investigation was performed with the participation of Combustion Engineering, Inc. (CE), subcontractor to FBNML, for the express purpose of improving the manufacturability of the magnet design and providing a revised schedule and cost estimate reflecting the expertise of a heavy equipment manufacturer.

The starting point for the investigation was the ETF magnet system conceptual design prepared early in 1981 by FBNML and described in System Design Description SDD503, contained in the CDER[1].

The major objectives of the investigation were to:

a. Identify improvements in the magnet design from the manufacturability standpoint.

b. Prepare a manufacturing plan and schedule (including on-site work) for the magnet assembly, incorporating the design improvements identified.

c. Prepare a cost estimate for the magnet system, based on the improved design and the manufacturing plan developed.

The manufacturability study and associated cost estimating work by CE pertained only to the magnet assembly itself. The water-cooled warm bore liner, roll-aside subsystem and other accessory subsystems were not included in CE's assigned task. In arriving at a revised cost estimate for the overall magnet system, as discussed below, the revised estimated cost (by CE) for the magnet system itself was combined with the original estimated costs (by FBNML) for other components of the system as included in the overall system cost estimate breakdown[2] of March 13, 1981.

The magnet fabrication and assembly costs contained in this report were estimated by CE using FBNML (conceptual) drawings similar to those included in SDD503 of the CDER[1], but updated to include improvements for manufacturability. Costs of material, shop labor, on-site labor, tooling, etc. were itemized for each component. In this respect, the estimate contained in this report represents a more thorough and detailed effort than the FBNML estimate contained in the CDER[1], where costs were scaled from estimated costs obtained by FBNML in connection with previous investigations of larger (commercial size) magnets. However, it was not possible, with the limited time and funds provided for the present study, to prepare detailed manufacturing drawings, to make special cost-reduction studies, and to make fully detailed estimates. Any future program to advance MHD toward commercial status should therefore include further effort in magnet engineering and costing. This work should extend the existing conceptual designs into the next level of design complexity to allow the manufacturing and assembly aspects of construction to be considered in more detail with subsequent upgrade of cost estimates.

3.1 SUMMARY

During the initial phase of this preliminary manufacturability study, the original magnet conceptual design presented in SDD503 was reviewed and revisions were made to simplify its fabrication. These revisions are discussed in Section 3.3.3 of this report and drawings incorporating the revisions are contained in Attachment B. A manufacturing plan, schedule, and cost estimate were then prepared by CE, based on the revised design. The CE report on their work is included as Attachment A to this report.

To minimize overall costs, the manufacturing plan is based on maximizing the work done in the shop (manufacturer's plant), within the economic constraints of delivery of the components to the plant site (assumed to be Montana).

The two halves of the saddle magnet winding, each in its own helium vessel, will be completed in the shop, including vacuum-testing of the vessels. The halves, each weighing about 225 tons, will be shipped separately to the plant site where they will be joined in a special assembly fixture. Superstructure and cryostat parts will be shop fabricated and delivered in modular form for final assembly at the site.

The revised schedule, made by combining FBNML's original estimated schedule[2] for conductor and substructure procurement with the schedule developed by CE for fabrication and assembly of all other major parts, shows installation of the magnet on-site completed 37 months after start of contract. Allowing 6 months additional for magnet evacuation, cool-down and shake-down test (the same as in the original FBNML schedule), the total time is 43 months. This is an improvement on the original schedule[2] prepared by FBNML in March, 1981, which showed a total time of 45 months. Schedules are discussed in more detail in Section 3.4.

The magnet cost estimate made as a part of the manufacturing study (based on work by CE) showed the installed cost of the magnet, including on-site tools and fixtures, but not including design and analysis, special on-site costs and contingency, was $22,669,000, compared to $28,472,000 based on the FBNML estimate[2] of March, 1981.

The complete updated magnet system estimated cost, made by combining the revised magnet estimated cost with the original FBNML estimated cost for the balance of the system (roll-aside track and actuator subsystem, other support subsystems, shake-down test) and including design and analysis costs, special on-site costs and contingencies, amounts to $49,400,000. compared to the figure of $57,666,000 estimated in March, 1981. The revised cost estimate is discussed in more detail in Section 3.5.

3.2 CONCLUSIONS

a. The magnet design utilizes construction and assembly techniques that are suitable for the larger magnets required for commercial size (500 to 1000 MWe) MHD/steam power plants.

b. The design concept avoids the necessity for large precision machine tools. The machining operations can be performed either on subcomponents or with portable tooling.

c. Design tolerances permit the use of as-welded structures with only a minor amount of grinding or surface preparation anticipated.

d. The design and the manufacturing plan minimize on-site fabrication and assembly labor.

e. The CE estimated cost of the installed magnet assembly is substantially lower than the earlier FBNML estimate contained in the CDER.[1] The reduction may be attributed in part to design improvements for manufacturability and to more detailed estimating procedure. However, since drawings supplied to CE were not complete in all details and since experience has shown that manufacturing cost estimates vary substantially with source, the CE estimate should not be regarded as superseding earlier estimates, but rather should be considered together with earlier estimates in determining the probable range in which the magnet cost for the ETF will lie. (See Section 3.5)

3.3 DISCUSSION

3.3.1 Evolution of the ETF Magnet Conceptual Design

The basis for the conceptual design of the ETF superconducting magnet which is the subject of this study was the conceptual design of a larger (commercial size)

MHD magnet referred to as the "CSM" design, started by FBNML in 1979, and originally conceived as a scale-up of the CDIF superconducting magnet[3] design. The work on the CSM design was a part of FBNML's overall MHD magnet technology development program, which included the preparation and evaluation of several reference (conceptual) design commercial-size MHD magnets. Although evaluations are not yet complete, the CSM design appears to be the most suitable for early commercial scale and ETF size magnets.

The original CSM design concept incorporated a rectangular saddle coil configuration and pancake-type windings in which individual conductors were supported in grooves in an insulating substructure. The conductor was thus kept free of accumulated magnetic loads, and the potential magnitude of mechanical disturbances at conductor surfaces was minimized. The conductor was bath-cooled and large passages were provided in the substructure to accommodate the liquid helium coolant. The superstructure and helium vessels were of stainless steel. All these features were common with the CDIF magnet design and were believed to contribute both to the reliable operation and ease of manufacture. (These features were ultimately retained in the ETF magnet design.)

As the CSM design progressed, it departed from the CDIF in several respects because of the difference in scale. These departures included the following:

a. Circular cable-type conductor was used in place of the rectangular built-up conductor (copper bar type) employed in the CDIF magnet.

b. The substructure was made up of a large number of small molded glass-reinforced pieces instead of the continuous G-10 plates with machined grooves as used in the CDIF magnet.

c. The helium containment vessel was closely fitted around the windings, with superstructure located outside the vessel in the vacuum space. This contrasted with the CDIF magnet design in which the superstructure was fitted directly on the windings and helium vessel outer walls surrounded the superstructure.

All three CSM features listed above were introduced mainly to facilitate manufacturing and to reduce costs.

Drawings were made of the CSM winding, containment vessel, superstructure and general assembly. They show the two halves of the winding enclosed in a single containment vessel, and an all-welded superstructure closely integrated with the containment vessel (in an effort to reduce amount of material). With this design, it was assumed that the coil container would be fabricated in part on-site, the coils would be wound into the container on-site, and a substantial amount of on-site welding would be required to close the vessel and complete the superstructure.

The design was reviewed for manufacturability with engineers and manufacturing representatives of Pittsburgh Des Moines Steel Co. As a result, it was decided to change the design (for improved manufacturability) such that a major portion of the superstructure was in the form of I-beams and threaded tie rods, which could be shop-manufactured and then assembled around the containment vessel with minimum on-site labor, thereby reducing cost.

The ETF magnet design, as described in the CDER[1] (SDD503), is a scaled-down version of this CSM design. Subsequent revisions are described in Section 3.3.3.

3.3.2 Alternative Concepts

Alternative design concepts which may be considered for the ETF magnet include the square bore concept[3] developed by Magnetic Corporation of America in 1977, the circular-bore "Cask" concept[4] developed by General Dynamics under FBNML sponsorship, the circular-bore, cylindrical-layer concept represented by the CFFF magnet[5] built at Argonne National Laboratory, the 1978 Avco Everett Research Laboratory ETF design[6], and the roll-apart concept[7] proposed by Avco Everett Research Laboratory in 1981.

The evaluation of these concepts, together with the CSM concept and others developed at FBNML, is a continuing activity and has not yet reached the point where any one design can be finally identified as most suitable.

A preliminary study of magnet/power-train interfacing,[8] carried out by FBNML early in 1981, with assistance from Avco and MEPPSCO, indicated that the rectangular bore is quite suitable for channel installation and generally permits better utilization of the high magnetic field volume produced by the magnet coils than does the circular bore. However, the detailed characteristics of applications and power train designs will, of course, influence final selection of bore shape in particular cases.

In choosing the rectangular bore and rectangular saddle coil concept (non-roll-apart) for presentation in the CDER[1], FBNML was influenced by the following factors:

a. The rectangular bore, rectangular saddle coil concept appears to be generally superior from the standpoint of magnetic volume utilization.

b. In our opinion, the rectangular saddle coil concept as represented by the ETF magnet design described herein is easy to manufacture and is favorable from a cost standpoint, as compared to other designs considered to date.

c. We expect that designs without substructure will present problems relative to the accumulation of local em loads and transmission of them to the superstructure, when scaled to commercial size; therefore, a substructure is considered essential.

d. The roll-apart concept has not been tried in a superconducting magnet and has not yet been investigated in depth. It is therefore considered too developmental for the ETF.

3.3.3 Revisions to ETF Magnet Design to Improve Manufacturability

During the review of the ETF magnet design by CE, starting early in 1981, revisions were made to upgrade the design and further facilitate manufacturing. These changes included the following:

a. The winding containment vessel was divided into two separate vessels, one for each winding half. Because of this change, windings can now be installed in the shop for cost saving. (The revised design provides that the two vessels, with windings installed, will be shipped separately from shop to site, where they will be joined and liquid helium cross-connections, vent stack, etc. added. Shipping both halves together as a unit would be impractical because of the very large overall dimensions).

b. Lifting lugs were added to large components to facilitate assembly.

c. Main support struts were canted to provide for a wider support base.

d. Winding pattern was revised so that fewer special substructure pieces are required.

e. Winding exit-end substructure crossovers and corresponding container parts were enlarged to provide adequate room for power-leads.

f. Exit-end stack was eliminated, to reduce cost.

g. Inlet-end stack and liquid helium reservoir were enlarged to provide larger helium reserve and facilitate assembly.

h. Greater clearance was provided between vacuum jacket outer shell and cold parts to facilitate assembly. (Jacket diameter increased).

i. Vacuum jacket heads were changed to flat plates instead of plates with curved (radiused) outer edges, to reduce cost.

j. Vacuum jacket side covers were eliminated to reduct cost. (The revised design provides for entire top half of jacket shell to be a separate module, removable by grinding welds.)

3.3.4 Drawings

A set of 15 drawings, included as Attachment B in this report, show the ETF 6 T magnet components as revised during this study.

Because of limited time and funding available, it was not possible to prepare revised general assembly drawings, outline drawings, etc.

The overall diameter of the magnet, as revised, is 30' (compared to 27' 6" originally). The overall length remains unchanged.

3.4 REVISED SCHEDULE, 6 T MAGNET SYSTEM

The critical path schedule for magnet system manufacture and installation, based on the CE estimate of time required for magnet major parts fabrication, is shown in Fig. 3.1. The total time through shake-down test is 43 months, which is shorter by 2 months than the estimated schedule[2] prepared by FBNML in March, 1981.

It should be noted that the CE schedule contained in their Manufacturability Report, Attachment A, allows an extra 3 month period at the start for design (manufacturing drawings) of the conductor and substructure, which was not included in the FBNML schedule of March, 1981. With this extra time included, the total critical path time amounts to 45 months (the same as in the original FBNML schedule[2]) and there is a waiting period of 2 months in the coil container schedule. It is reasonable to assume that a major part of conductor and substructure manufacturing drawing work can be done during the design and analysis phase of the project. Based on this assumption, 2 months can be deducted from the overall schedule and the total time shortened to 43 months, as shown on the revised schedule, Figure 3.1.

3.5 REVISED COST ESTIMATE, 6 T MAGNET SYSTEM

The revised cost estimate for the magnet system, incorporating the new CE estimate for magnet fabrication and assembly but retaining substantially the same estimates for other elements of the system (accessories, roll-aside equipment, etc.) as appeared in the original FBNML estimate[2], is presented in Table 3.1, Summary Cost Estimate and Table 3.2, Cost Estimate Breakdown.

It should be noted that the CE estimate for the magnet used the same costs of conductor, substructure and internal instrumentation as used in the original FBNML estimate[2]. Costs of coil containers, structure, cryostat, assembly, etc. were new estimates made directly by CE using FBNML revised drawings.

The CE estimates showed reductions in (shop) manufacturing cost of about 500 k$, in on-site tooling of about 1500 k$ and in on-site installation of about 3500 k$ (not including design and analysis, special on-site costs and contingency).

FIGURE 3.1
CRITICAL PATH SCHEDULE
ETF 6 T MAGNET SYSTEM (REVISED)

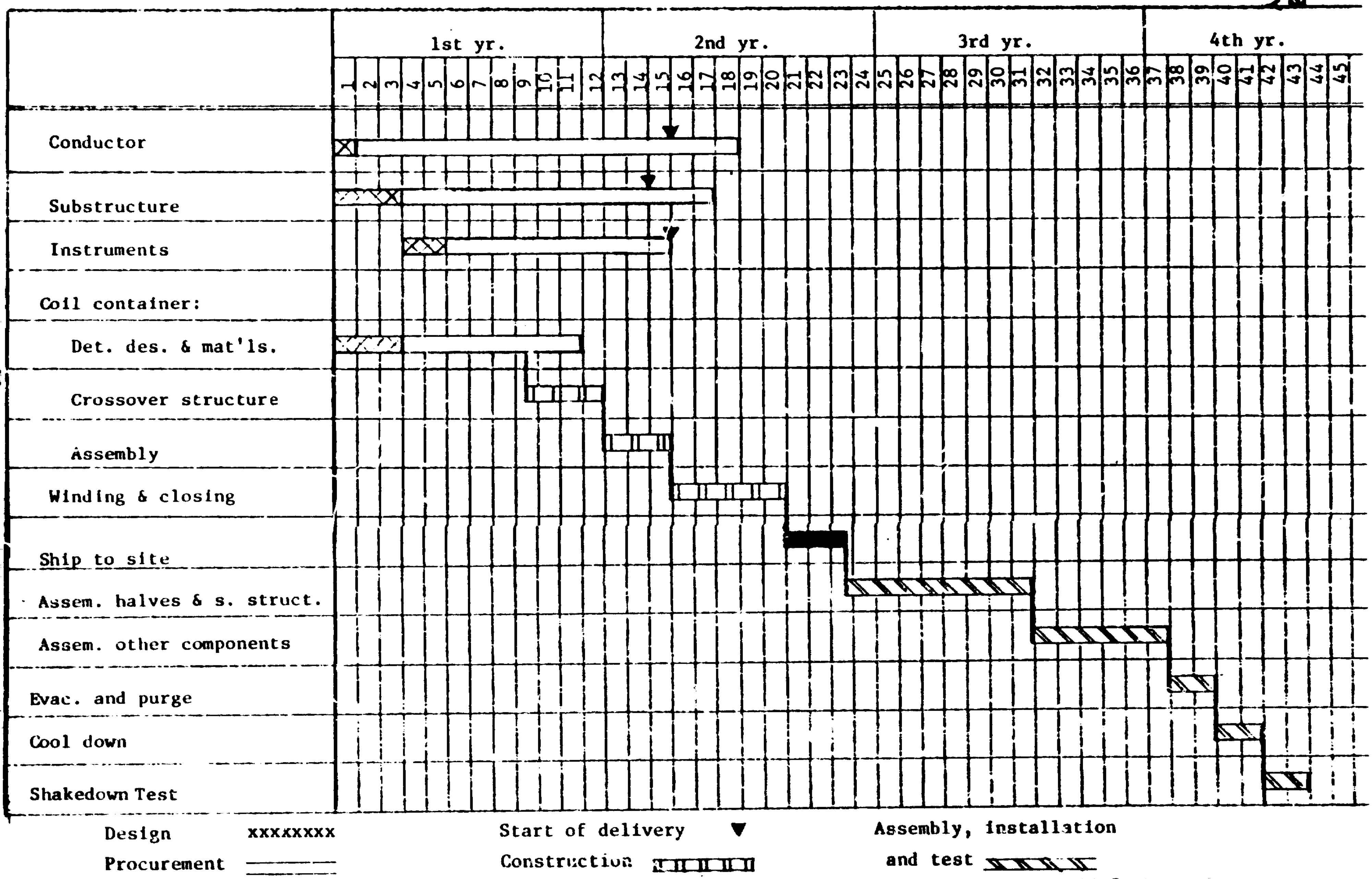

TABLE 3.1

SUMMARY COST ESTIMATE[1,2]

ETF 6 T MAGNET SYSTEM

CONCEPTUAL DESIGN (REVISED)

ACCT. NO	ACCOUNT DESCRIPTION	QUANTITY	MATERIAL COST		INST. COST	INDIR COST	CONTIN	TOTAL COST
			MJF COMP	BOA				
317.3	MAGNET SYSTEM	1	31,383	80	2,975	298	9,984	44,720
	ENGINEERING SERVICES (FIELD)	-	-	-	2,921	-	584	3,505
	OTHER COSTS	-	-	-	985	-	197	1,182
	TOTAL ESTIMATED COSTS	-	31,383	80	6,881	298	10,765	49,407

[1] This cost estimate does not include fo ndations.

[2] Costs are K$, 1981

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TABLE 3.2

COST ESTIMATE BREAKDOWN[1,7]

ETF 6 T MAGNET SYSTEM - CONCEPTUAL DESIGN (REVISED)

ACCT. NO.	ACCOUNT DESCRIPTION	QUAN.	DESIGN & ANAL.	MAT'L & MFG	SHOP ENG'G	PACK & SHIP	MATERIAL MFR COMP	COST[2] BOA	INST COST	INDIR COST	ENG'G SERV. 8	OTHER COST	CONTIN.	TOTAL COST
317.3.1	Magnet assembly													
317.3.1.1	On-site tools						356		0					
.2	Roll-aside track						621		150					
.3	Wind. contain vessels[3]						15,521		987					
.4	Main structure						5,118		Incl. above					
.5	Cold mass supp. struts						717		Inc. below					
.6	Therm. rad. shield						591		120					
.7	Vacuum vessel						3,676		738					
.8	Warm bore liner						839		80					
	Total magnet assembly						27,439		2,075	208	2,520	850	8,917	38,639
317.3.2	Support subsystems													
317.3.2.1	Hydro. actuator sys.						128		30					
.2	Cryogenic supp. system						1,536		250					
.3	Power supply & dis. sys.						1,152		150					
.4	Main vacuum pump sys.						256		70					
.5	Utility boom, contr., misc.						640		100					
	Total support system						3,712		600	60	350	118	874	5,246
317.3.3	Magnet shakedown test						232	80	300	30	51	17	193	835
Total	Total						31,383	80	2,975	298			9,984	44,720
	Engineering Services										2,921		584	3,505
	Other cost											985	197	1,182
317.3	TOTAL												10,765	49,407

1 This estimate does not include foundations.

2 Material cost is FOB site.

3 This item includes conductor, coil winding (in shop) and shop assembly.

4 Includes 100 K$ eng'g. test supervision and analysis.

5 Includes liquid nitrogen and liquid helium.

6 On-site technician labor cost.

7 Costs are K$ mid 1981.

8 Field engineering

These substantial reductions can be attributed in part to design improvements for manufacturability and to the fact that the GE estimates were made by experienced manufacturing people based on ETF magnet component drawings, whereas the earlier estimates[2] were made largely by scaling from budgetary estimates of larger magnet costs and may have been overly conservative. However, since drawings supplied to GE by FBNML were not complete in all details and since it is known that estimates made by different manufacturers tend to vary considerably, the estimates discussed in this report should be considered preliminary and subject to further revision when more detailed design and estimating is accomplished. It is our recommendation that until more comprehensive estimates are made, the ETF magnet system budgetary cost be taken as in the range from $\$50 \times 10^6$ to $\$60 \times 10^6$ (median $\$55 \times 10^6$).

3.6 REVISED WEIGHT ESTIMATE, 6 T MAGNET SYSTEM

The estimated weight of the magnet assembly based on the updated design and more detailed estimating procedure used in this study is about 2,200,000 lbs., as compared to 2,000,000 lbs. listed in SDD501. A part of the increase results from redesign of the vacuum vessel base to provide more conservative stiffness and structural strength. The balance of the increase is attributable to a more detailed estimating procedure.

References

1. Conceptual Design Engineering Report (CDER) MHD-ETF 200 MWe Power Plant, September, 1981, prepared by Gilbert/Commonwealth, Engineers/Consultants for National Aeronautics and Space Administration, Lewis Research Center and U. S. Department of Energy, Fossil Energy, Office of Magnetohydrodynamics DOE/NASA/0224-1 NASA CR 165452, Volumes I through V.

2. Letter from A. M. Hatch (FBNML) to J. A. Burkhart (NASA LeRC) dated March 13, 1981 with the following enclosures:

   Summary Cost Estimate, ETF Magnet System Rev. 3/13/81

   Cost Estimate Breakdown, ETF Magnet System Rev. 3/13/81

   Schedule - Manufacturing and Installation, MHD-ETF 200 MWe Power Plant Magnet System (2 sheets) 3/2/81

3. Conference Paper,"Status of the CDIF Superconducting Magnet", R. L. Rhodenizer, et al, General Electric Co., Proceedings of the MHD Magnet Design Conference, MIT, Cambridge, MA, March 1980.

4. Final Technical Report, "Cask Commercial Demo Plant MHD Superconducting Magnet System - Conceptual Design . . . .", S. L. Ackerman, et al, prepared for MIT/FBNML by General Dynamics Convair Division, December 1979.

5. Conference Paper,"The Fabrication Experiences and the Performance Test of the Coal-Fired Flow Facility Superconducting Dipole Magnet", S. T. Wang, et al, Argonne National Laboratory, 19th Symposium, Engineering Aspects of MHD, the University of Tennessee Space Institute, Tullahoma, TN, June 1981.

6. Report, "Design and Cost for the Superconducting Magnet for the ETF MHD Generator", J. L. Zar, AVCO Everett Research Laboratory, Inc., April 1979, prepared for MIT/FBNML.

7. Private communication, J. L. Zar, AVCO Everett Research Laboratory, Inc. to A. M. Hatch, MIT/FBNML dated May 27, 1981.

8. Conference Paper, "Magnet-Flow Train Interface Considerations", P. G. Marston, A. M. Dawson, A. M. Hatch, MIT/FBNML; T. R. Brogan, MEPPSCO, Inc., 19th Symposium, Engineering Aspects of MHD, the University of Tennessee Space Institute, Tullahoma, TN, June 1981.

9. Letter from J. M. Tarrh, MIT/FBNML to J. A. Burkhart, NASA LeRC dated April 6, 1981 confirming agreement on definition of tasks under NASA LeRC Grant NAG-3-100.

10. Final Report, "Design of Superconducting Magnets for Magnetohydrodynamics (MHD) Applications", R. J. Thome, et al, prepared for DOE (formerly ERDA) by Magnetic Corporation of America, June 1977.

ATTACHMENT A

Manufacturability Report

MHD-ETF 200 MWe Power Plant Magnet System

Conceptual Design

prepared for

Massachusetts Institute of Technology
Francis Bitter National Magnet Laboratory

by

Combustion Engineering, Inc.

September, 1981

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Manufacturability Report

MHD-ETF 200 MWe Power Plant Magnet System

Conceptual Design

1.0 INTRODUCTION

The manufacturability of the magnet and vacuum vessel of the MHD-ETF 200 MWe Power Plant Magnet System has been investigated by Combustion Engineering, Inc. The magnet concept was designed by the Massachusetts Institute of Technology, Francis Bitter National Magnet Laboratory (MIT-FBNML).

The magnet assembly included in this report consists of two saddle coils in their helium vessels, the thermal shields surrounding the superconducting coils, and the vacuum vessel in which the magnets are located. MIT-FBNML retained responsibility for estimating the design and analysis, the substructure, conductor, instrumentation, structural supports, the supporting cryogenic systems, and the system for moving the magnet assembly to one side for maintenance. The warm bore liner, electrodes, etc., are not included. The components are as described in the Preliminary System Design Description, SDD-503, Magnet System for Magnetohydrodynamics Engineering Test Facility Conceptual Design-200 MWe Power Plant.

The magnet system design accommodates construction and assembly techniques that are suitable to the larger magnet systems required for a commercial size (1000 MWe) MHD/steam power plant. (The ETF size permits completion of the magnet halves in the shop with barge and truck delivery to Butte, Montana.) The design concept avoids the necessity for large precision machine tools. The machining operations can be performed either on subcomponents, or with portable tooling. The design tolerances permit the using of as-welded structures with only a minor amount of grinding anticipated.

The general manufacturing plan is based on maximizing the work done in the shop within the economic constraints of delivery of the components to Butte, Montana. The two saddle magnet coils will be completed in the shop, including vacuum testing of the helium vessels with temporary closures. The superstructure parts (beams and tie rods) will be completed and delivered to the site for assembly. The thermal shields and vacuum vessel will be shop fabricated and delivered for final assembly at the site. The detailed description of the elements of this plan follow.

1.1 Materials

The materials selected by MIT-FBNML are 316LN stainless steels for the cold mass structures Type 6061 aluminum alloy for the thermal shields and 304L stainless steel for the vacuum vessel. The surfaces of materials are not polished for vacuum service. Grain size determination and Charpy impact testing have not been required. Fracture toughness testing of the 316LN material is required in certain critical areas to be defined later. (The mill has declined to quote on performing testing at 4.2K.) Physical properties are not required at 4.2K, but will be determined to enable selection of best materials for critical areas of design. The plates are to be ultrasonically tested. Based on the above requirements the type 316LN plate was quoted at $2.50 per pound, the type 304L plate at $1.77, and aluminum 6061 alloy at $1.77 per pound. The cost of testing at 4.2K has not been included in these quotations.

1.2 Magnet Coil Cases (Helium Vessels)

The magnets are encased in Type 316LN stainless steel structures that also serve as liquid helium vessels. The two magnet cases are made as left- and right-hand parts to accommodate the helium piping upon assembly. The two cases can be fabricated in parallel operations, but shipping considerations and field assembly place both halves on the critical path. Shop fabrication is based on the following subcomponents.

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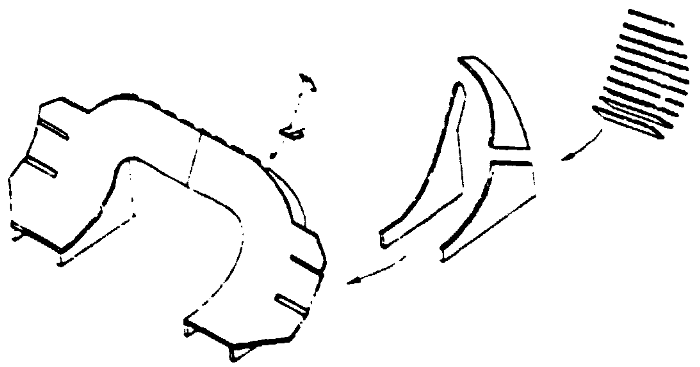
2 - Outlet Crossover Subassemblies
2 - Inlet Crossover Subassemblies
4 - Base Plate Subassemblies
2 - Inner Side Plate Subassemblies
2 - Outer Side Plate Subassemblies
2 - Sets of Cover Plates

CROSSOVER SUBASSEMBLIES



The four crossover subassemblies are on the critical path, with the larger (outlet ends) units requiring the greater effort. The crossover subassemblies support the conductor and substructure as it passes around the gas flow ducts. The forces are large, requiring short spans between supporting gussets. The three-inch thick base plate is extended beyond the conductor box to permit attachment of supports incorporated into the superstructure. The resulting dimensions (151" x 253" and 136" x 230") exceed the dimensions of plate obtainable from the mill, requiring two pieces for each base plate. Before the two pieces are joined by butt welding, they are formed to a 60 degree templet and the excess material removed by burning. The support pieces and gussets are also cut to dimensions and two pieces are formed to follow the outer edge of the crossover bends. The four crossovers require 222,600 pounds of material to be ordered, with 135,670 pounds in the completed parts. There are 184 feet of 2-inch welds and 35 feet of 3-inch welds, requiring over 1370 pounds of weld wire.

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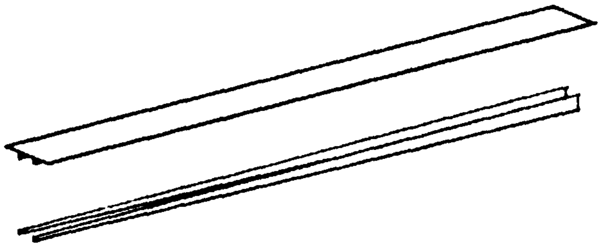
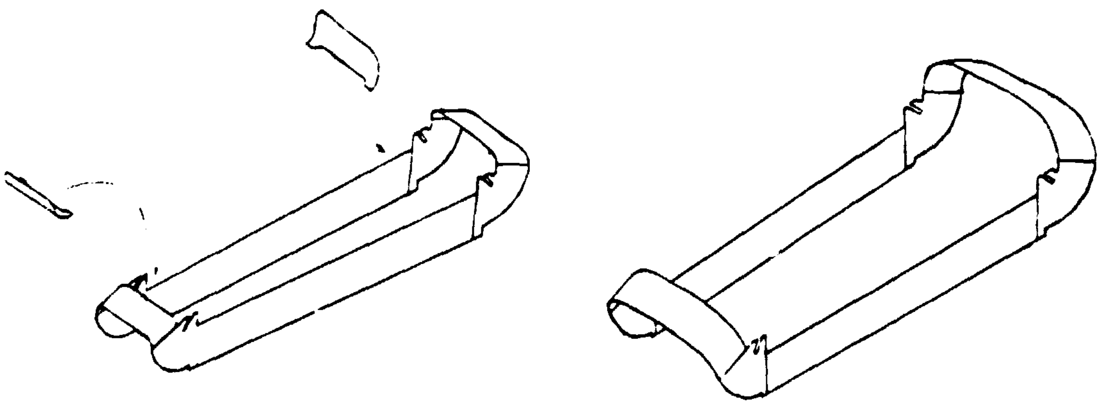
BASEPLATE SUBASSEMBLIES



The baseplate subassemblies space the crossovers at the proper distance. These four simple subassemblies require 68,300 pounds of type 316LN stainless steel to be ordered. Due to the tapered supports, only 48,375 pounds remain in the finished parts. The tapered support welded to the base plate do not require full penetration welds. The 576 feet of welds require only 512 pounds of weld wire. These subassemblies are joined between inlet and outlet crossover subassemblies using full penetration welds. This assembly operation establishes the overall dimensions and alignment of each magnet half.

SIDEPLATE SUBASSEMBLIES



The inner and outer sideplate assemblies are made from six pieces. The long straight sides are 2" plate. The transition plate and crossover pieces are 3" plate. The side plates accommodate the widening

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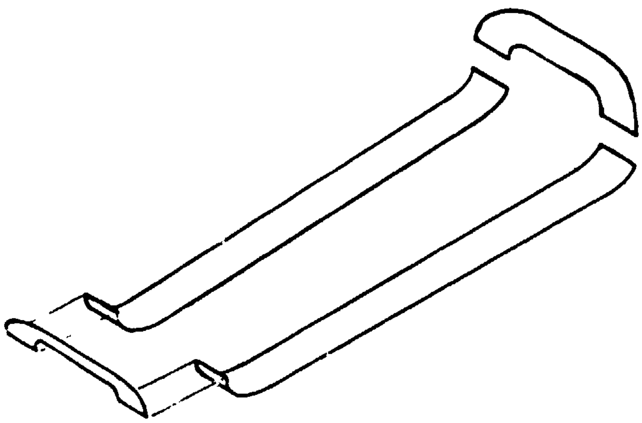
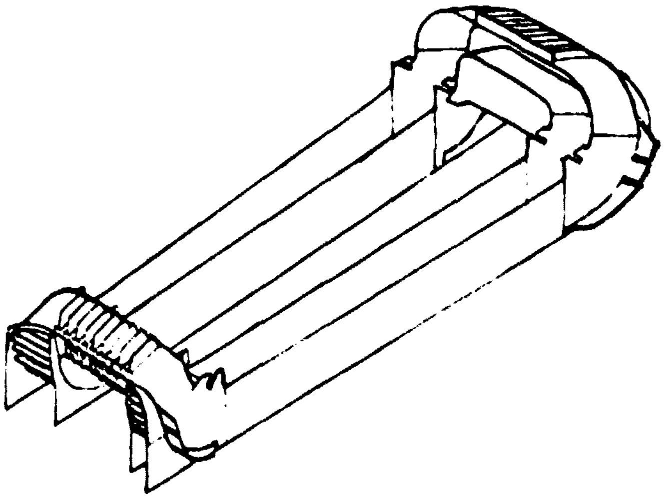
of the magnet halves from the inlet to outlet ends. The material ordered weighs 254,409 pounds. The finished pieces weigh 235,040 pounds. The required weld length is 190 feet. The transition plates are machined for required fit-up, with slots for the cross coil superstructure beams, and with holes for helium, electrical leads, and instrumentation access. The inner assembly has a "filler plate" welded at each end. The filler plate distributes the end load from the crossover windings into the side plates. The fit-up and assembly of these parts to the structure forms the open box into which the substructure and conductor will be placed.

COVER PLATES



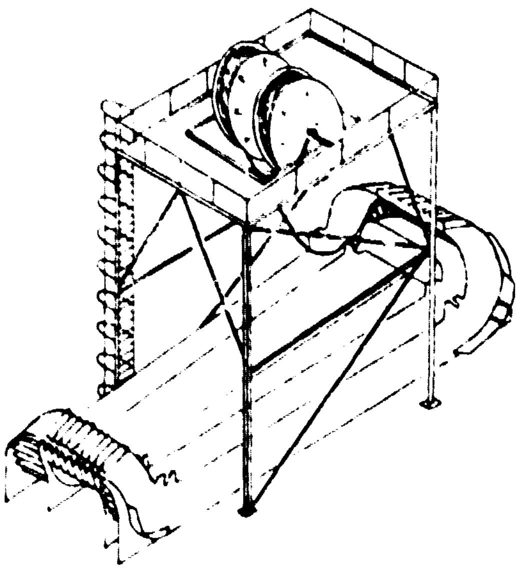
The preparation of two sets of cover plates is not on the critical path, as they are not required until after the winding operations are complete. The cover plates cannot be prewelded, as the configuration of the crossovers creates an "overhand" for an assembled cover plate. The cover plate parts are relatively simple, consisting of two long pieces with formed ends to fit the sixty degree bend at the crossover, and two flat plates shaped to the inlet and outlet crossovers, with allowances of excess material for removal during final fit-up.

SUBASSEMBLY



During assembly of the side plates to the structure, the squareness and straightness of the space for the conductors will be continuously verified. The next critical path operations are the assembly of substructure and winding of the conductor. A fixture will be made to support two reels of conductor above a half magnet. The conductor box will be prepared by cementing ground plane insulation to the base plate and sides. In this operation, any unevenness of the surfaces will be corrected by filling, or grinding of excess material.

WINDING OF CONTRACTOR



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The winding of conductor is preceded by placement of two perforated tubing loops into the substructure grooves. The stainless steel tubing is used to distribute helium gases during controlled cooling and heating of the cold mass from and to room temperature. The introduction of these tubing loops and of the conductor requires the outlet crossover to be wider and deeper than the inlet crossover and special pieces of substructure to be used. The conductor lead is fed out of the channel into the helium "stack" space where it is coiled for shipment of the magnet to the site. With the tubing loops and conductor lead in place, the remaining substructure for the first layer of conductor is installed. In this first layer, only four turns are placed prior to a splice between this Grade A conductor and the Grade B conductor. The splices used in the magnet are mechanical assemblies compressing the ends of each grade in a copper block.

The winding of the twenty turns of Grade B conductor proceeds to complete the first layer. The first layer is completed with the conductor at the outside of the outlet crossover. At this time the second layer of substructure is placed and bolted to the first layer pieces. In-process tests are conducted. The winding of the second layer proceeds from the outside toward the inside of the coil. When seventeen turns of Grade B conductor are placed, a splice to Grade A conductor is made. Succeeding layer pairs are placed in a similar sequence. The location of the splice between conductor grades steps toward the outside of the coil, with the last eight layers being wound with only Grade A conductor. The last layer is wound from the outside to the inside of the coil. Special substructure blocks are added to carry the conductor lead across the top of the bundle. The lead end is fed through the bushing in the case and coiled for storage during shipment to the site. As the conductor is wound into the substructure, the internal instrumentation is applied as required. The instrument leads are carried out through bushings and coiled for shipment.

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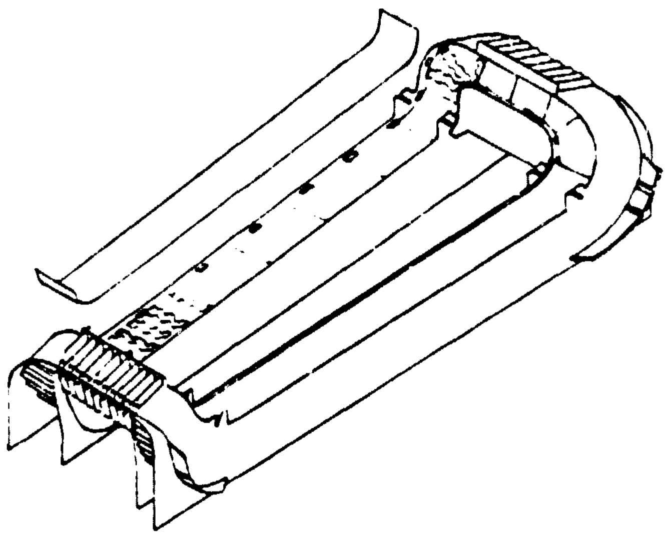
CLOSING COIL CONTAINER



When all layers of conductor and all internal instrumentation have been completed, the ground insulation panels are placed atop the conductors and substructure. Although each layer of substructure is bolted to the next lower layer, the entire bundle will be spring loaded to preload the assembly when the cover plates are applied. The springs are placed, and the cover plates fitted. A group of compression jacks are used to preload the conductor bundle through the cover plates and the plates are tack welded. When all plates satisfy the requirements, welding is completed, including the butt joints between cover plate pieces.

At this stage, temporary covers are welded into the helium openings, and the vessel is vacuum tested. Final shop inspection is made, and any of the superstructure beams that will not interfere with shipment are added. Both coil halves are packaged for shipment and, with other components, will be shipped by barge to the west coast.

1.3 Magnet Superstructure

The design of the superstructure consists of beams and tie bolts to equilibrate the repulsive magnetic loads, with intercoil beams and ties welded to the crossovers to transfer those loads into the helium vessel. Due to the expansion of the gas through the magnet, the dimensions of the beams and tie rods increase continuously from the inlet to outlet ends. Furthermore, due to this taper, only one flange on each beam can be square to the

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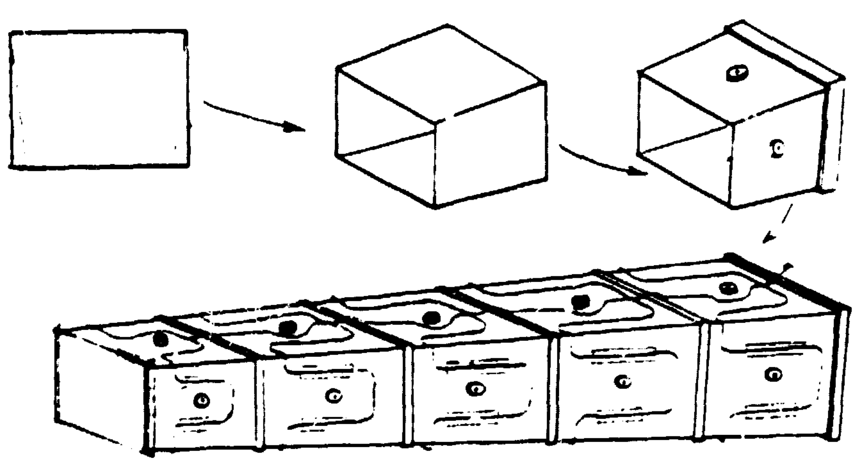
web. The 56 beams are made from 257,500 pounds of type 316LN stainless steel plate and 57,000 pounds of Type 316LN stainless steel pipe. The 56 studs weigh from 3005 pounds to 3350 pounds each. The 112 nut and washer sets weigh 175 pounds each. There is 1390 feet of welding required to make the beams, 980 feet of which can be machine welded. The miscellaneous superstructure associated with the crossover weighs over 63,750 pounds. Except for the beam across the sixty-degree bend line of the crossovers, all the superstructure is added when the two halves are joined at the site.

1.4 Thermal Shield

The thermal shield intercepts heat radiated through the space from the vacuum vessel walls toward the liquid helium cooled magnet and structure. The shield consists of 3/8 inch thick aluminum sheets with liquid nitrogen filled tubing attached as needed. The sheeting is surrounded on both sides by mirrored mylar film insulation layers.



The inner thermal shield is a truncated pyramid that fits between the warm bore of the vacuum vessel and the helium vessels of the magnet. It is made of five short sections that assemble with tongue and groove joints. Each of the sections has cooling tubing attached. The nitrogen distribution and collection headers are installed after assembly in the field. Each of the sections is attached to the warm bore of the vacuum vessel before this assembly is inserted into the magnet. The mirrored mylar insulation is also positioned during the site assembly of the vacuum vessel.

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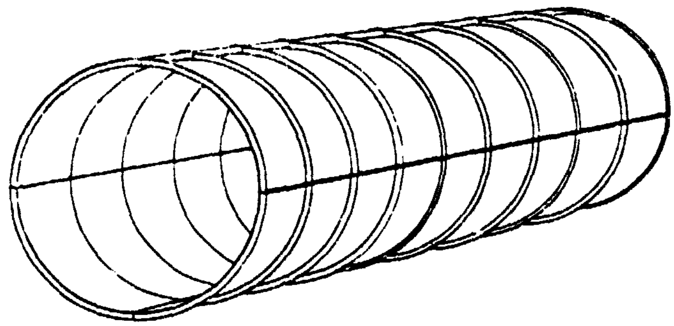
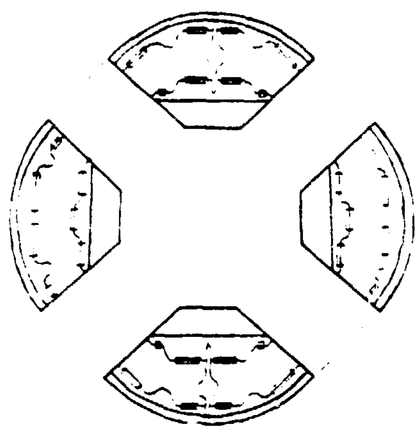


The outer thermal shield consists of 32 quarter rings. These pieces are joined by insulated bolted flanges. The stainless steel nitrogen cooling lines are not electrically insulated at these joints. The lines are joined after the cylinder is assembled. The cylinder is 350 inches (29 ft 2 in) in diameter and fifty-two and one-half feet long.



The two heads are each made in four pieces again using electrically insulated flange joints. The heads are attached to the outer thermal shield. The assembly is hung from the lower half of the vacuum vessel. A pair of "V" struts attach the two center rings to the outershell and act to center the assembly during cool-down and heat-up. The remaining rings are simply supported to permit differential expansion.

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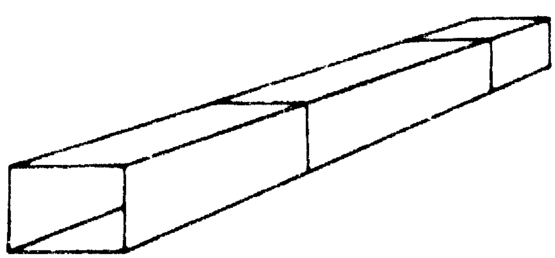
1.5 Vacuum Vessel

The vacuum vessel is designed to operate at room temperature and to maintain a vacuum of 10^{-8} torr without the cryogenic temperature components being in service. The vessel is 383.5 inch diameter over the stiffener rings and 56 feet long. The vessel consists of truncated trapezoidal-shaped "warm bore", with flat plate heads and a ring reinforced cylinder. In order to maximize shop fabrication to accommodate the assembly sequence and to meet material handling problems, the vacuum vessel is made in the following sections:

1	Warm Bore	90" x 116" x 660"
2	Heads	2 - 98" x 307" subassemblies
		1 - 146" x 340" subassembly
		2 - 73" x 279" subassemblies
		1 - 171" x 340" subassembly
1	Outlet End Support Box	120" x 340" x 155"
1	Inlet End Support Box	120" x 340" x 135"
12	Cylindrical Panels	4 - 128" x 624" panels
		4 - 128" x 348" panels
		4 - 107" x 138" panels

1.5.1 Warm Bore



The warm bore is a truncated trapezoid some 55 feet long with ends of 120" x 145" tapering to 67" x 82". The thickness of the warm bore varies from 3" at outlet to 2" at inlet. Over 180,700 pounds of material must be ordered with the finished weight being 151,282 pounds.

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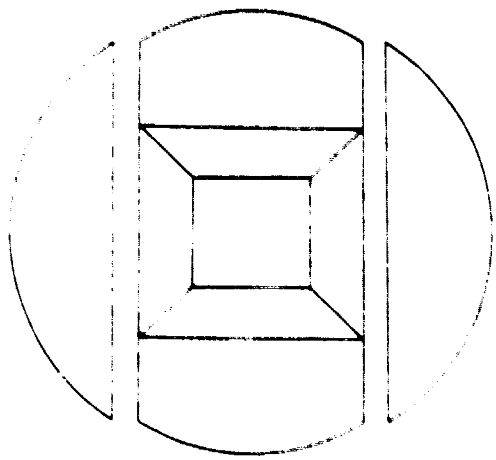
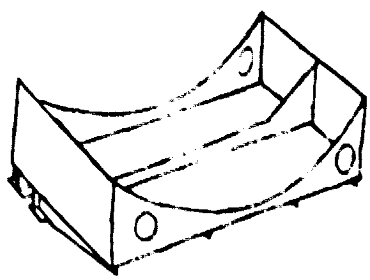
1.5.2 Vacuum Vessel Heads



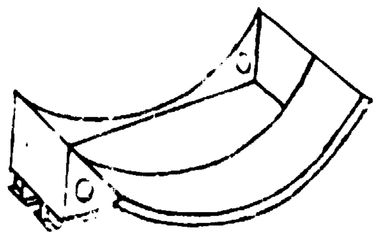
Each of the heads will be divided into three pieces for shipment to the field. Two sides of the head will be shipped as flat plates prepared for field welding. The center section will be a subassembly of the top and bottom plates joined to the transition sections. Of the 189,600 pounds of type 304L stainless steel purchased, 154,150 pounds remain in the finished heads.

1.5.3 Outlet Support Box



The support box structure at the outlet end of the vessel contains the pads for the main structural supports and two pads for carrying the axial and lateral seismic loads. The support box rests upon the cross beams on which the entire magnet is rolled aside some 34 feet to perform maintenance on the warm bore liner. The weldment is shop fabricated from 1-1/2" to 3" thick plate.

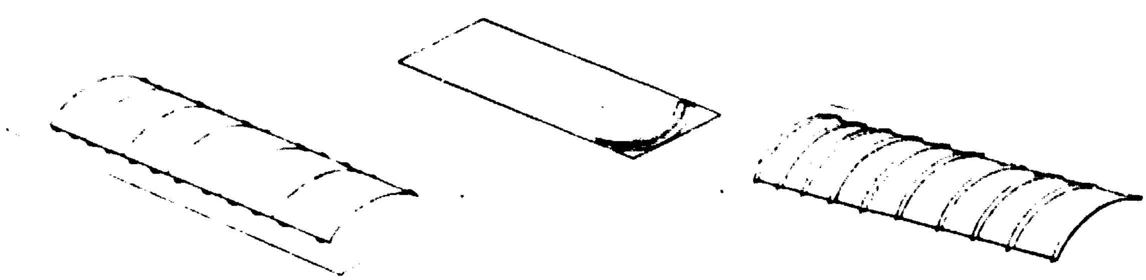
1.5.4 Inlet Support Box



At the inlet end, the support system accommodates the shortening of the cold mass during cooldown. Therefore, only the two main structural support columns and one lateral load support are included. The inlet box subassembly is shorter than the outlet box, as there are no axial load columns involved. A portion of cylindrical shell is attached to make up the dimension to the head flange. The inlet box rests upon a set of cross beams as does the outlet box. The weldment is shop fabricated.

1.5.5 Cylindrical Panels

There are twelve panels in the vessel, as required to accommodate shipping restrictions and the desired assembly sequence. These panels are prefabricated in the shop and shipped to the site. Four long panels are joined to make a half cylinder for the top of the vessel. The remaining panels are joined with the support boxes to make the lower half of the vessel.



Material procurement affects the fabrication plans for the shell. The rolling of the 3/4 inch plate requires extra length on each piece to secure the curvature to the joint.

Transportation of the pieces from the mill to the shop sets a width limitation. Shipment of the panels to the site requires dividing the cylinder into eight long, curved panels.

The materials purchased for the shell weigh 182,343 pounds; for the flanges, 79,539 pounds. The width of the panels shipped is 147".

1.6 Cryogenic Stacks and Piping

The helium and nitrogen connections within the vacuum boundary will be prefabricated in the shop. The piping and fittings will be joined, but the subassemblies will be selected to provide materials for final fit-up at the site.

1.7 Shipment

Since the weight and size of the saddle coils exceeds normal rail limitations, the delivery of the ETF magnet by barge and truck has been proposed. The necessary detailed investigation of clearances and bridge weight limits has not been made for this study. The experience of C-E's traffic department in delivery of nuclear reactor components to remote sites is the basis for the route selection and delivery estimate included. The route involves shipment of all components from the shop on one barge to a west coast port. From that point, the components would be transported to the site by special trucks. The necessary work to relocate overhead lines and reinforce culverts and bridges as required has been included in the packing and shipping estimate of 1,734,000.

1.8 Site Assembly

Most of the site work consist of assembling the parts made in the shop. Parallel operations are permitted on the vacuum vessel assembly, the magnets and superstructure and the thermal shields. The critical path involves the magnet halves, superstructure, and assembly of all components. The C-E study did not include completion of the vacuum

system, cryogenic system, power system, controls for the magnet, or the site testing and checkout.

In order to insert the warm bore into the assembly, a fixture has to be used. This fixture consists of a beam around which the components are assembled. The fixture must be over twice the length of the assembly, in order to have its supports outboard of the assembly with the warm bore ready for installation. A 60 inch square beam of 1" and 2" plates with a length of 120 feet was conceived. During insertion of the warm bore (181,000 pounds) the beam will deflect about 3-1/4 inches. For economy, this beam was estimated based on carbon steel construction. Therefore it must be stored well away from the magnet during operations.

Each magnet half will be attached to ring supports on each end. The ring supports will permit orientation of the magnet for down hand welding of most joints. Two welding crews and one beam assembly crew will work on the assembly simultaneously for some eight months.

During this time, the vacuum vessel and thermal shield subassemblies will be joined to make up the vessel into lower and upper halves. The mirrored mylar insulation will be attached to thh inner thermal shield assembly. These operations are not on the critical path.

When the magnet assembly is completed, with the helium piping and the helium and nitrogen stacks attached, the assembly on the fixture will be raised and the lower half of the vacuum vessel moved on its tracks beneath the magnets. The magnet support system will be attached as the magnet is lowered into the vessel. The outer thermal shield will be attached to the assembly, with the superinsulation in place. The upper vessel shell will then be attached. Lowering of the upper shell onto the assembly is critical. The cryogenic connections are made through the vessel head, and the final movement of the head require precise positioning. At this time, the magnet is released from the fixture. The support of the fixture is changed to permit one vessel head to be fitted and welded to the vessel shell. The fixture supports are again changed permitting the warm bore and other closure head to be placed

thereon. This assembly is supported on the fixture at each end by adjustable, rolling supports. The assembly is carefully inserted through the magnet, and joined to the opposite head. The final closure of the vacuum vessel then proceeds.

After the conductor and instrumentation leads are connected to the external wiring, the cryogen systems are connected. The vacuum vessel is tested for leaks, and brought to specified vacuum specifications. The nitrogen system is retested, and cooldown of the cold mass begun. These tests are followed by testing of the magnet and checkout of all systems.

2.0 Cost Estimatation

Table 2-1 provides a tabulation of the estimated costs for the MHD ETF magnet. The costs for superconductor, substructure instrument and cold mass supports were estimated by MIT-FBNML. The total magnet costs of $22,459,000 are in 1981 dollars without any contingencies having been added. It is, of course, for a conceptual design that has not included many of the details required for a final design. This estimate is believed to provide an accurate base figure for requesting a project budget.

3.0 Critical Path Schedule

Figure 3-1 provides the preliminary critical path schedule for the MHD ETF magnet concept. The schedule assumes that detailed design and analysis of the magnet system has been completed prior to award of a contract to fabricate. Three months are provided to prepare shop drawings of the components sufficient for material procurement. The conductor material procurement times for conductor were provided by MIT-FBNML. Those for stainless steel are based on quotations from G. O. Carlson reflecting current mill capacity. The fabrication spans were a minimum in this estimate, as is proper for critical path determinations. The delivery of conductor became the critical path, followed by winding of the coils, closing the cases, and packing for shipment. Both coils are wound simultaneously, requiring two winding fixtures.

Table 2-1

COMPILATION OF ESTIMATED COSTS FOR MHD ETF MAGNET

	ENTRY ITEMS	Weight Installed, K pounds	Weight Purchased, K pounds	Special Tools, K$	Material Costs K$	Shop Labor Costs K$	Shop Eng'g. Costs K$	Total S.D.C. K$	Mfg. Costs Including G&A plus profit	Pack & Ship Costs K$	At-Site Costs K$	On-Site Tooling Costs	Assy. & Inst. Costs K$	Total Costs K$
1	Superconductor	226	262		6500	included in 5	in 5	6500	7507					
2	Substructure	180	200		950	included in 5	in 5	950	1097					
3	Instruments, Int. Piping				100	included in 5	in 5	100	115					
4	Coil Container Weldment	500	630		1574	192	66	1832	2116					
5	Winding and Assembly	-	-	174	-	343	117	584	675					
6	Subtotal - Magnet Coils	906	1092	174	9124	535	183	9966	11510	725	12225	235	987	13447
7	Superstructure	526	530		2048	862	295	3205	3703	415	4118		in 6	4118
8	Thermal Rad. Shields+Stacks	76	82		180	92	32	312	360	58	418	45	120	583
9	Cold Mass Supports	22	22		485	-	-	485	560	6	566		in 11	566
10	Vacuum Vessel	669	814		1656	364	125	2145	2477	530	3007		396	3403
11	Final Assy. & Installation	-	-		-	-	-	-	-	-	-	-	342	342
12	TOTAL	1293	1448		4377	1318	452	6147	7100	1009	8109	45	858	9012
13	TOTAL MAGNET	2199	2540		13501	1853	635	16113	18610	1734	20334	280	1845	22459
14	Tracks and Rollers													
15	Hydraulic Actuators													
16	Utility Boom													
17	Subtotal - Roll Aside Sys.										1538	-		
18	Warm Bore Liner	30									865	-	80	945
19	Cryogenic Support Systems													
20	Power Supply & Dist. Sys.													
21	Main Vacuum Pump Sys.													
22	Subtotal - Accessories										3238			
23	Instrumentation & Controls													
24	Shakedown Tests													
25	TOTAL													
26	Engineering Services													
27	Other, Total													
28	GRAND TOTAL													

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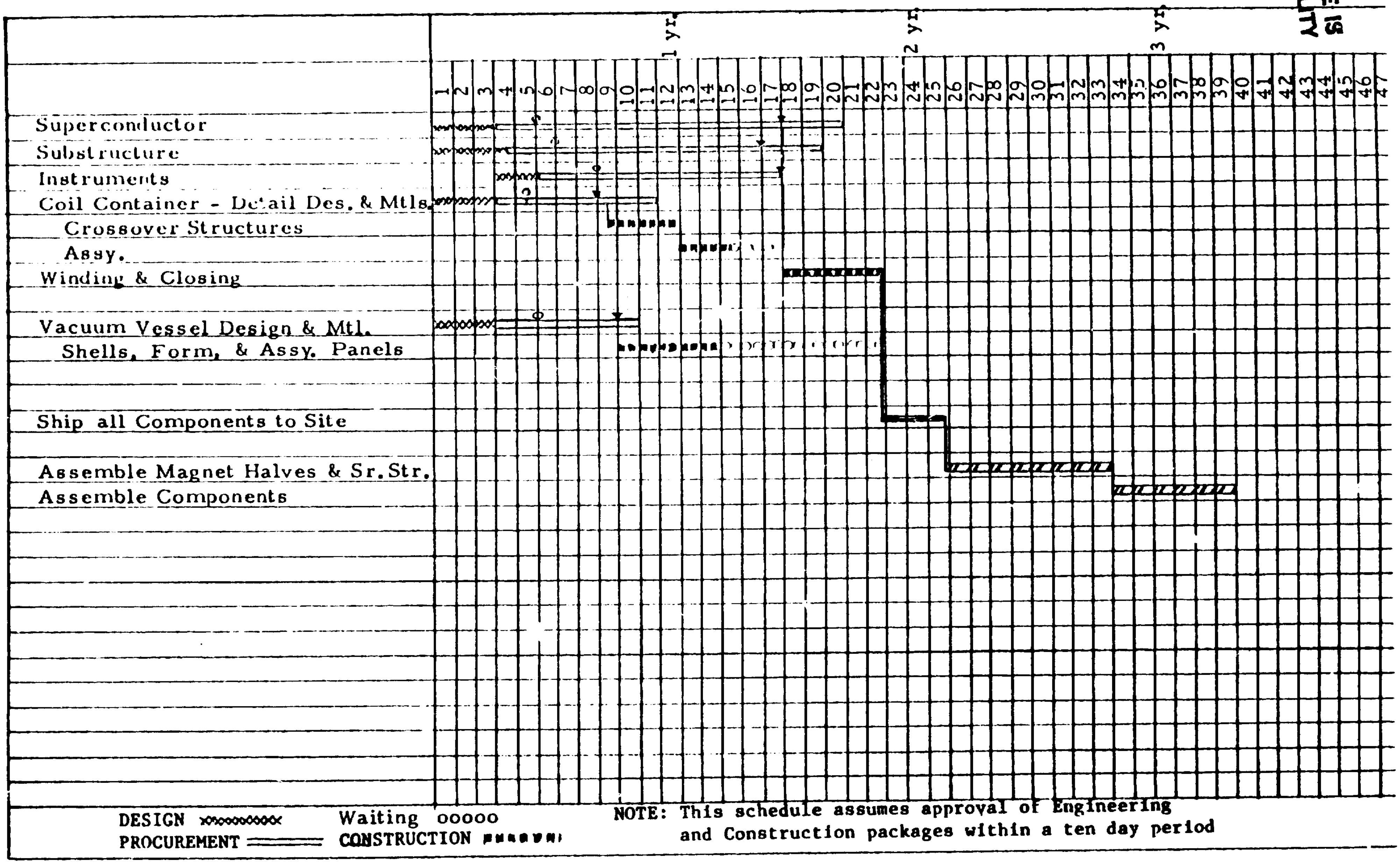
The delivery of all components by barge causes a "bottleneck". Site work cannot proceed, except on the assembly fixtures, until all components are delivered. At the site, the assembly of the cold mass is the critical patch. The vacuum vessel and thermal shield subassembly work can easily be performed during the eight months required to assemble the cold mass. Assembly of the other components and testing requires the remaining seven months.

Forty months from order placement appears to be an attainable schedule for the design concept studied.

FIGURE 3-1
PRELIMINARY SCHEDULE

MHD ETF MAGNET
CRITICAL PATH ONLY



NOTE: This schedule assumes approval of Engineering and Construction packages within a ten day period

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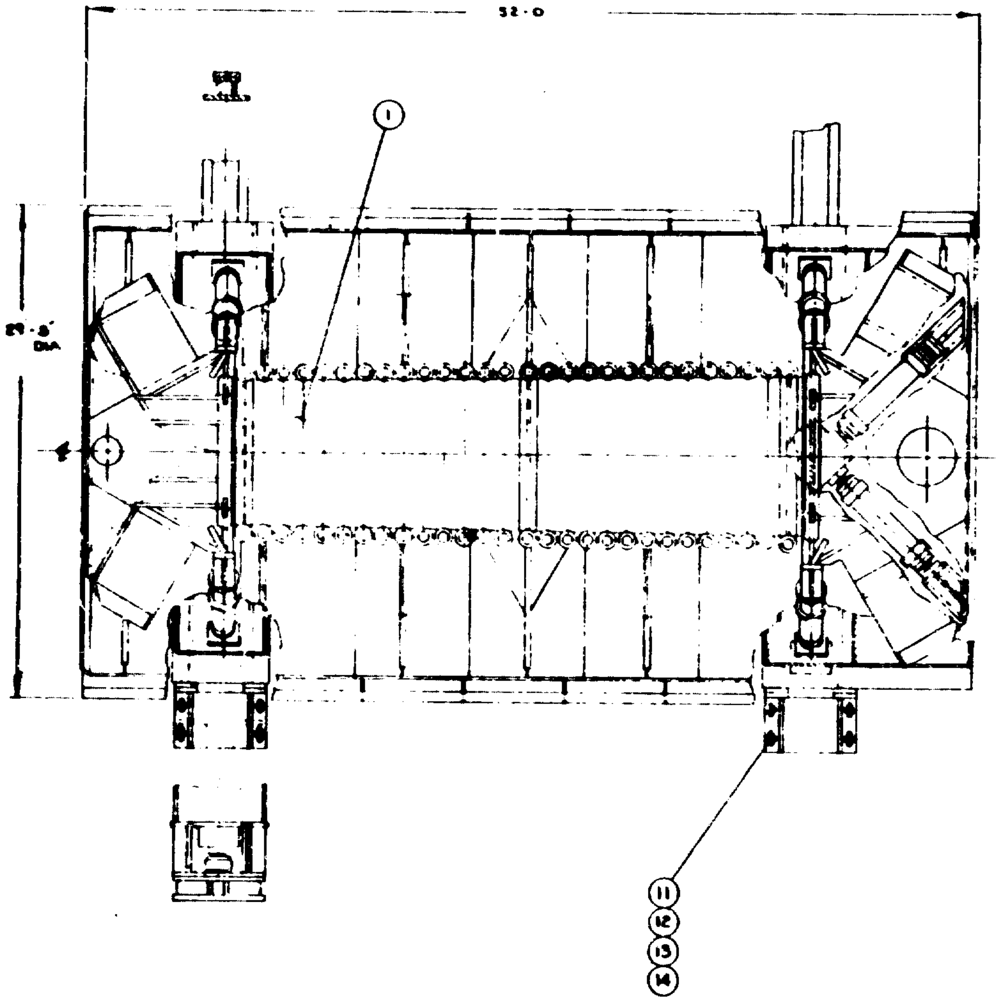
ATTACHMENT B

Drawings of ETF 6 T Magnet

Components (Revised)

The following drawings show magnet components that were revised to upgrade the design and improve manufacturability. The manufacturing schedule and cost estimate included in this report were based on the revised design as shown in these drawings.

J-4700-600	Sht. 1-4	Vacuum Jacket Base & Cold Mass Ass'y.
J-4700-601	Sht. 1-3	Cold Mass Assembly
J-4700-602	Sht. 1-2	Coil Container Assembly
J-4700-603	Sht. 1-2	Coil Container & Insulation Assembly
J-4700-604	Sht. 1-2	Coil Container Weldment
D-4700-605	———	Layer #2 Winding Detail
D-4700-606	———	Layer #3 Winding Detail
D-4700-607	———	Layer #26 Winding Detail
J-4700-613	Sht. 1-3	Outer Thermal Shield
J-4700-614	Sht. 1-3	Inner Thermal Shield
J-4700-615	Sht. 1-4	Vacuum Jacket Assembly
J-4700-616	Sht. 1-2	Service Stack Assembly
E-4700-300	———	Substructure Detail, Straight
E-4700-301	———	Substructure Detail, Corner
E-4700-302	———	Substructure Detail, Curved



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1	J-4700-601	COLD MASS ASS'Y		1	
2		VACUUM JACKET BASE WELDMENT		1	
3		THERMAL SHIELD LOWER HALF		1	
4		VERTICAL SUPPORT STRUT ASS'Y		4	
5		TRANSVERSE SUPPORT STRUT ASS'Y		2	
6		HORIZONTAL SUPPORT STRUT ASS'Y		2	
7		HOLD-DOWN BRACKET		4	
8		ROLLER UNIT (HILLMAN 72)		4	
9		HYDRAULIC CYLINDER		4	
10		TRACK ASS'Y		2	
11		BOLT 3/4-4 x 10 LG		40	
12		NUT-HEX 3/4-4		40	
13		WASHER 3/4 I D		40	
14		LOCK-WASHER 3/4 I D		40	

REF. DWG J-4700-600 SHT 2, 3, & 4

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VACUUM JACKET BASE AND COLD MASS ASS'Y

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J-4700-600

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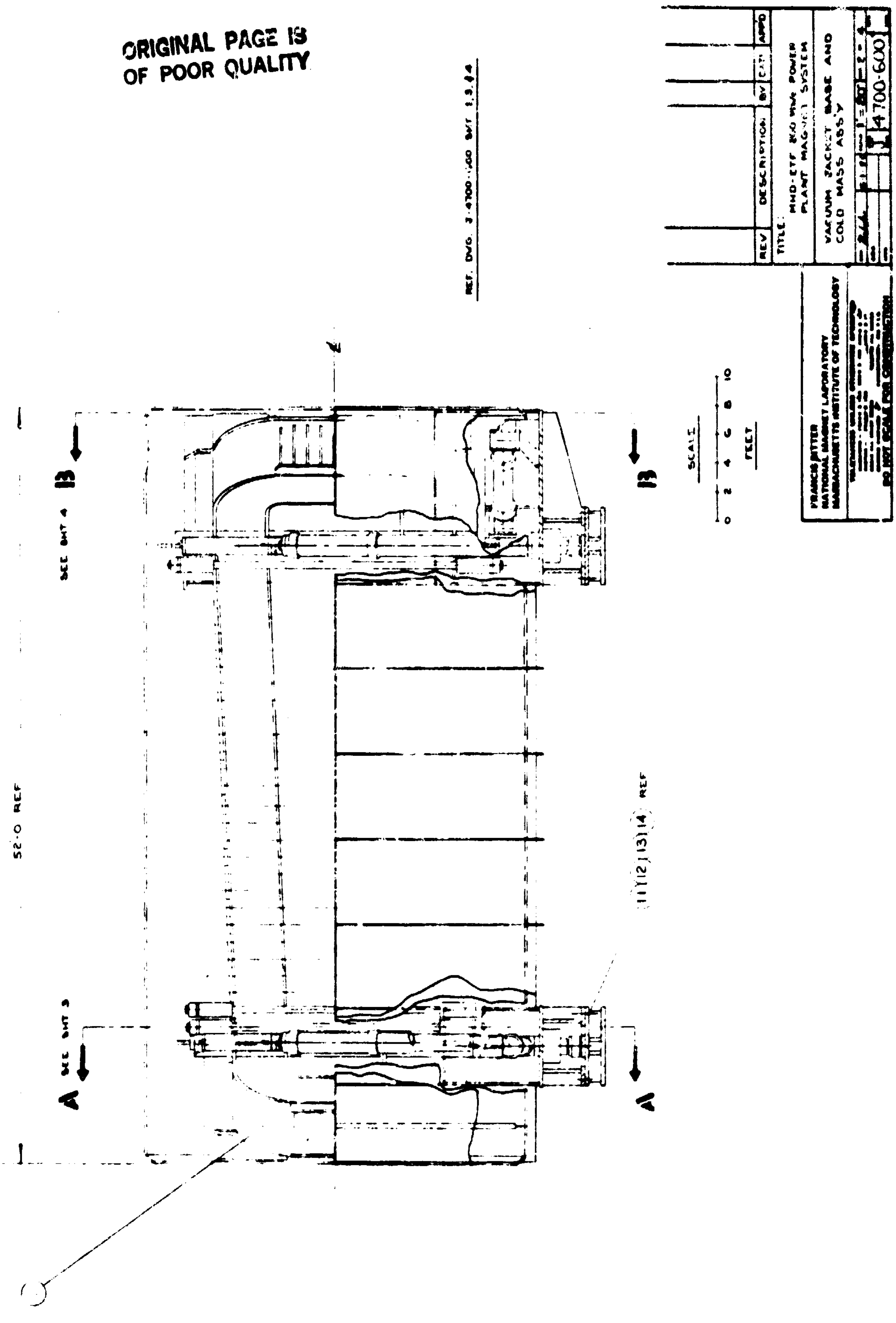

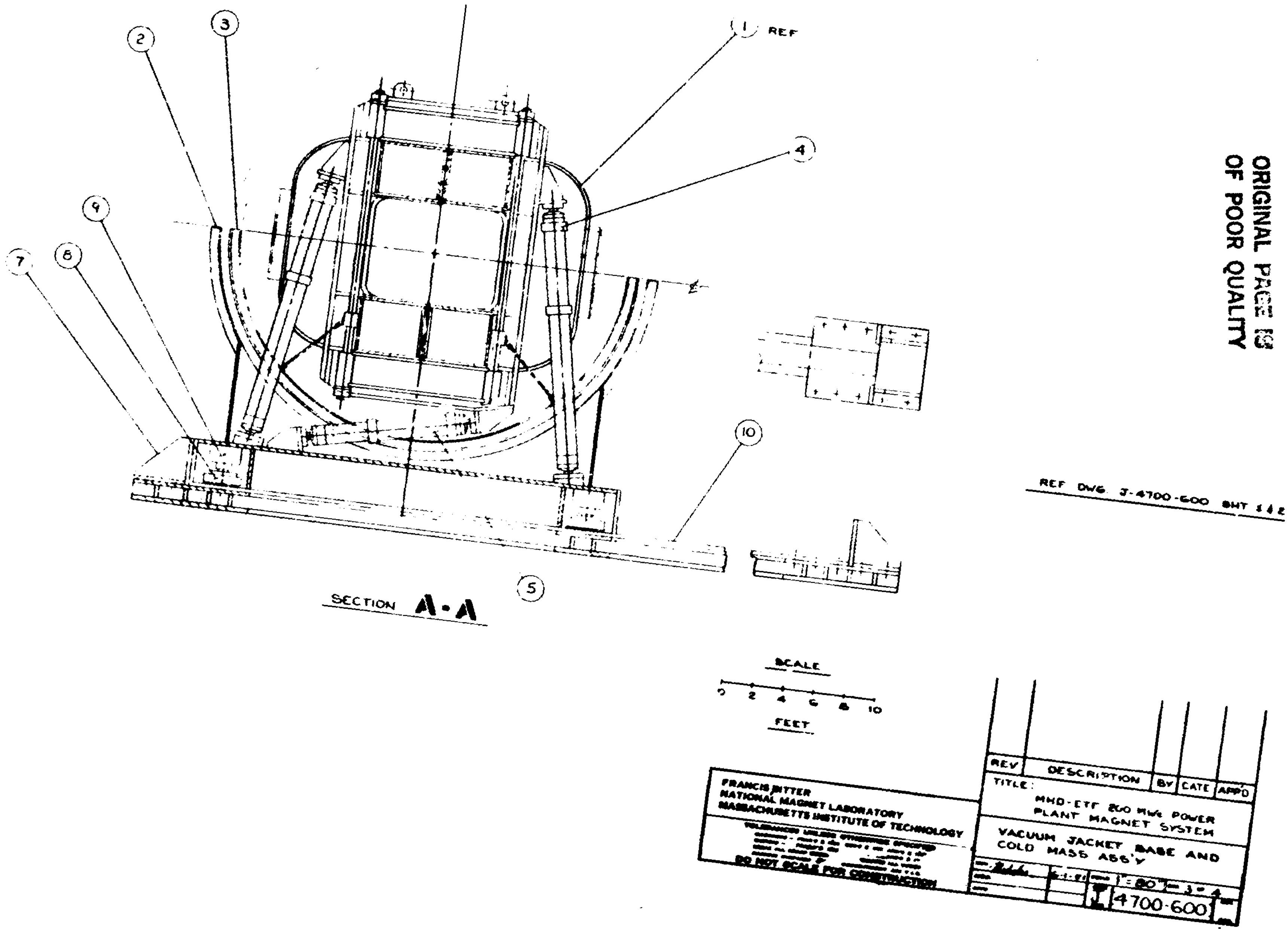
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DATE
APP'D
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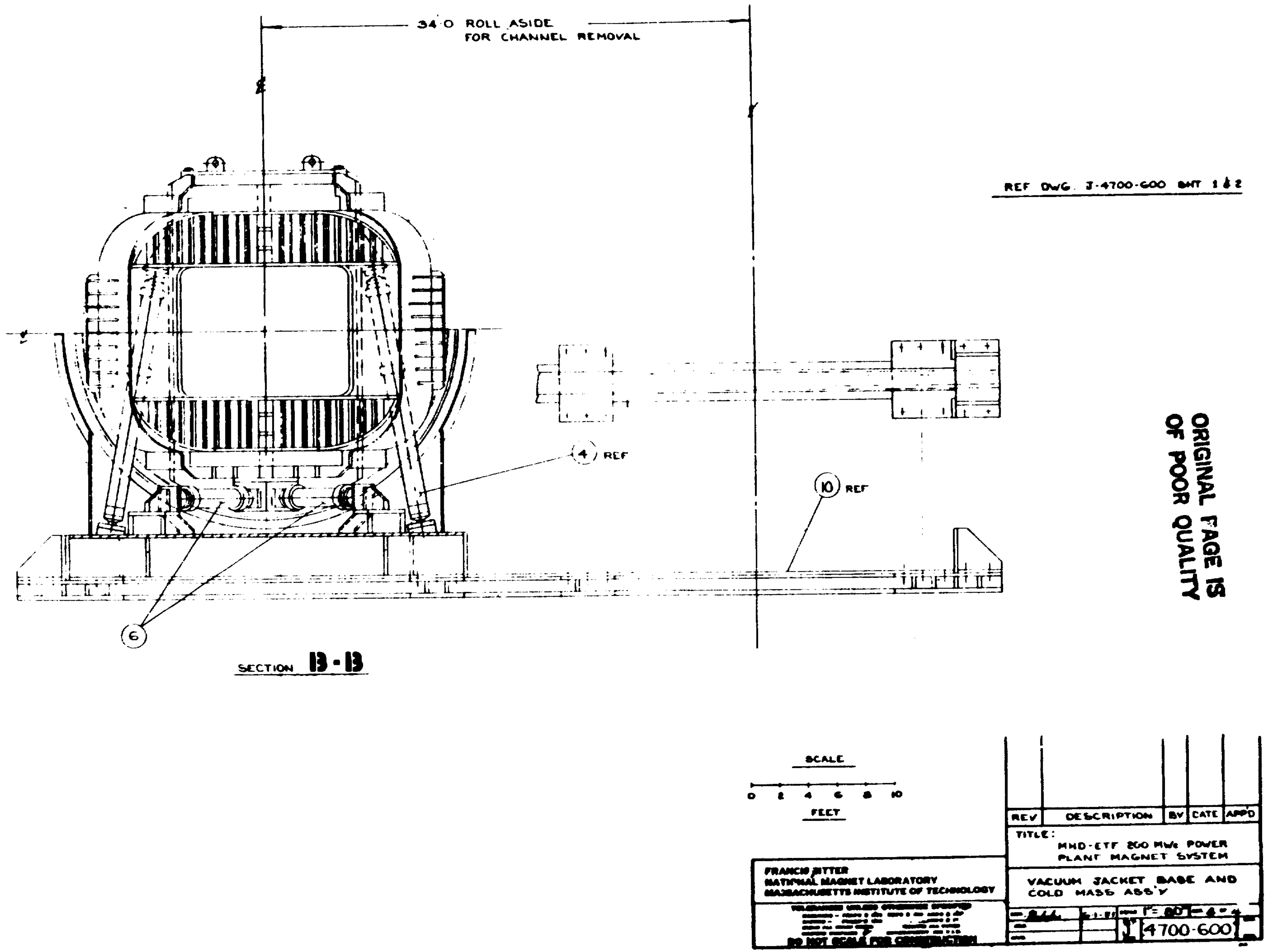
VACUUM JACKET BASE AND
COLD MASS ASS'Y
1"=80"
3-4
4700-600



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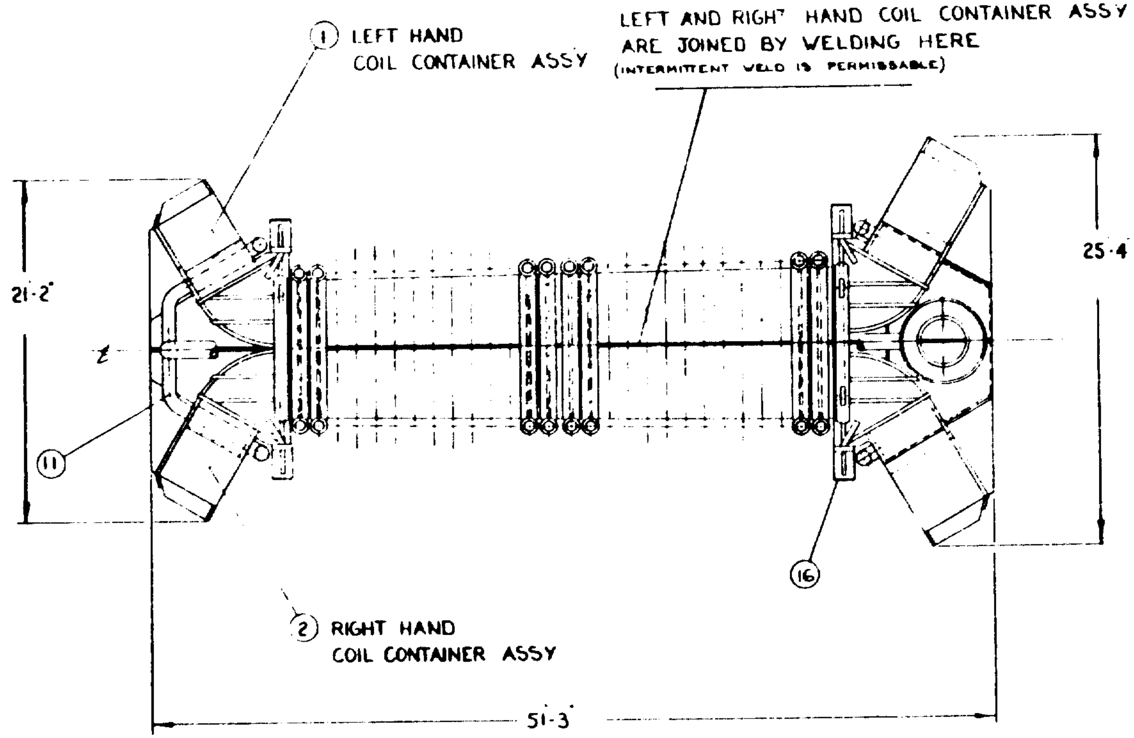

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3		I BEAM		56	
4		TIE ROD		56	
5		NUT		112	
6		SPHERICAL WASHER		112	
7		SPECIAL I BEAM INLET END		2	
8		SPECIAL I-BEAM OUTLET END		2	
9		SHELL FOR ACCESS			
10		PIPE 12 DIA x 48 FT LG			
11		PIPE 10 DIA x 9 FT LG		2	
12		PIPE 10 DIA x 10 1/2 FT LG			
13		LIFTING BRACKET		4	
14		BEAM - OUTLET END			
15		BEAM - INLET END			
16		VERTICAL STRUT SUPPORT BRACKET		4	
17		HORIZONTAL STRUT SUPPORT BRACKET			
18		TRANSVERSE STRUT SUPPORT BRACKET			

REF DWG 3·4700·601 SHT 2&3

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COLD MASS ASSY

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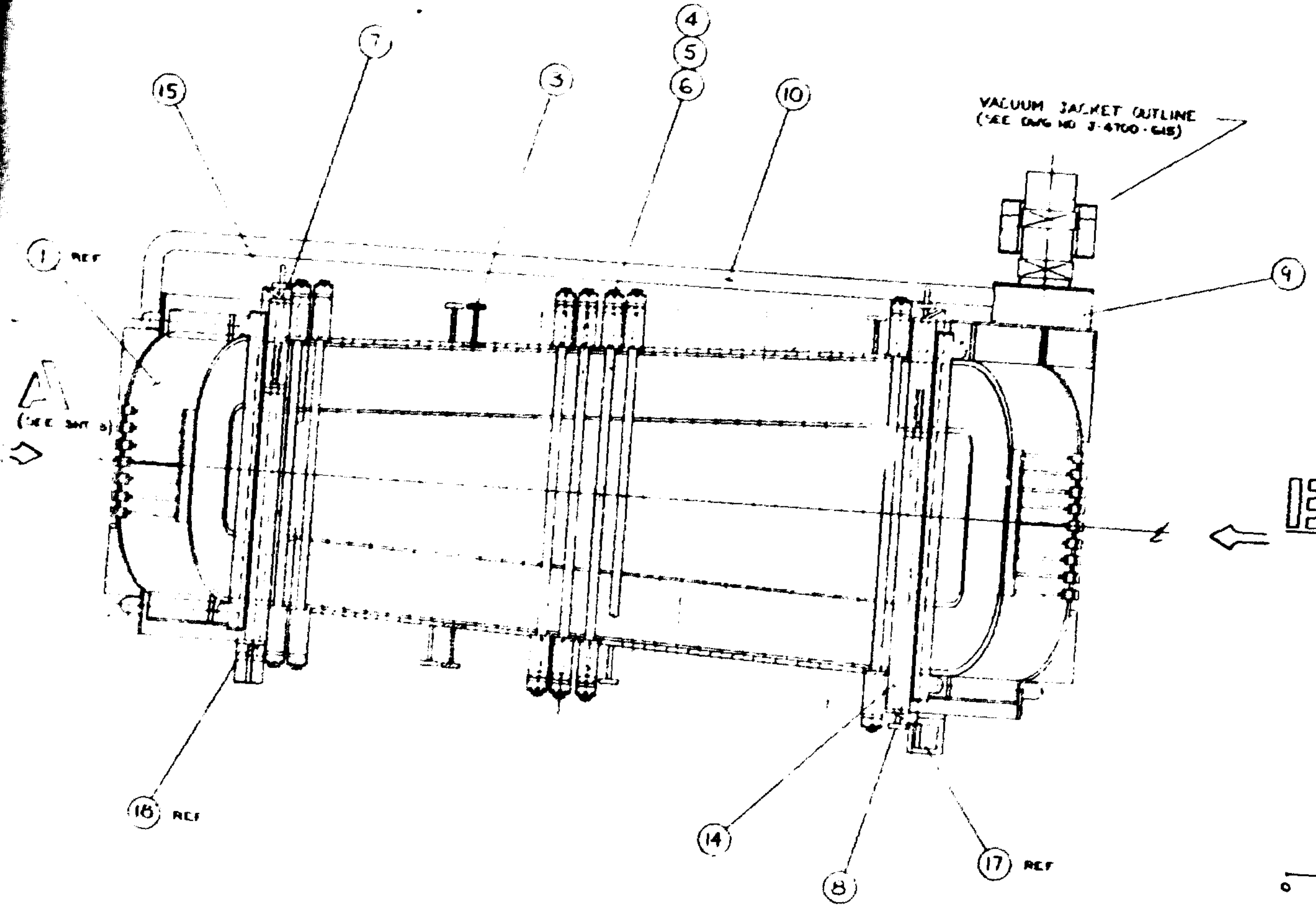

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TITLE: MHD-ETF 200 MWe POWER PLANT MAGNET SYSTEM

COLD MASS ASSY

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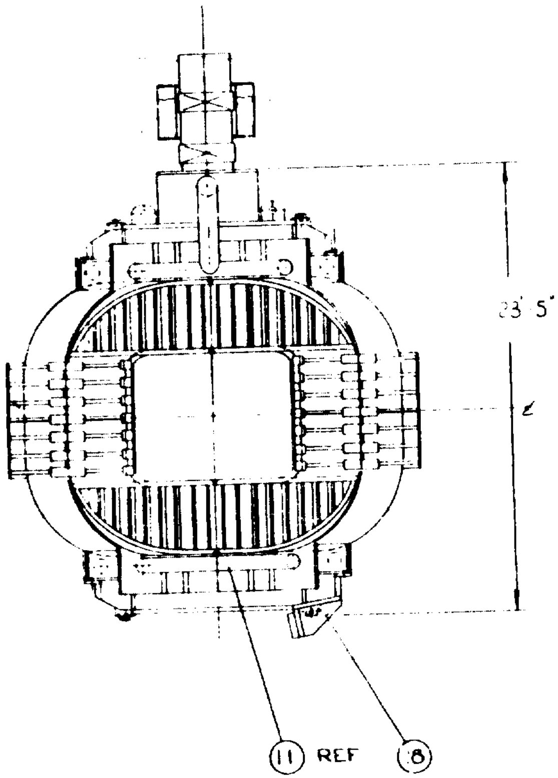

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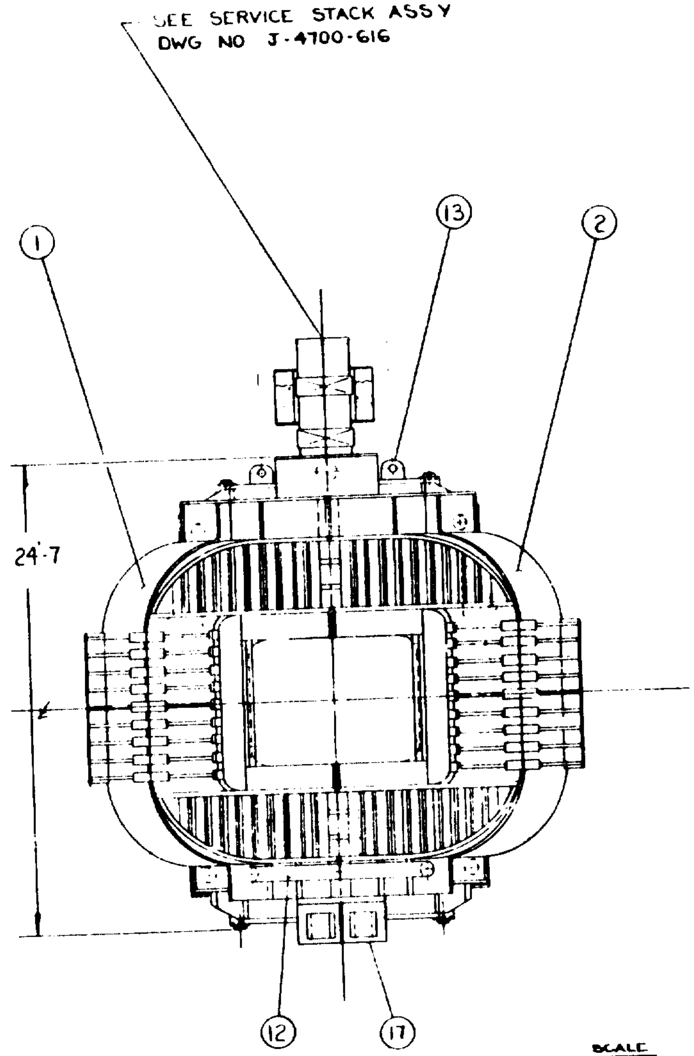

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TITLE: MHD-ETF 200 MWe POWER PLANT MAGNET SYSTEM

COLD MASS ASSY

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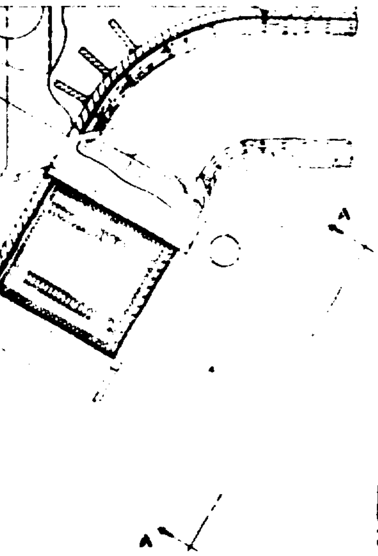

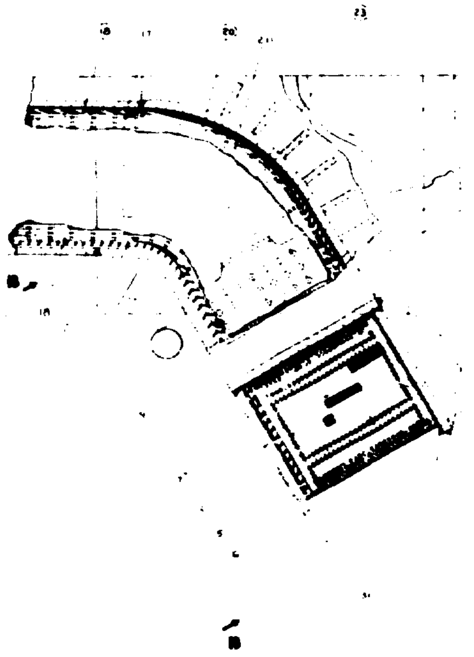

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4	[illegible]	INLET CROSSOVER REGION COVER PLATE	316 LN	1	
5	[illegible]	SPRING			
6	[illegible]	[illegible] PLATE	[illegible]		
7	[illegible]	[illegible] PLATE	[illegible]		
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10		CONDUCTOR LEAD CABLE [illegible]	[illegible]		
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NOTES

1. RIGHT HAND COIL CONTAINER ASSY SHOWN
   LEFT HAND COIL MIRROR IMAGE
2. ALL WELDS ARE HIGH VACUUM INTEGRITY WELDS
3. WELDING TO BE PERFORMED IN ACCORDANCE WITH ASME BOILER AND PRESSURE VESSEL CODE
4. NEXT ASSY DWG NO J-4700-601
5. REF DWG NO J-4700-602 SHT 2

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TITLE: MHD-ETF 200 MWe POWER PLANT MAGNET SYSTEM

COIL CONTAINER ASSY

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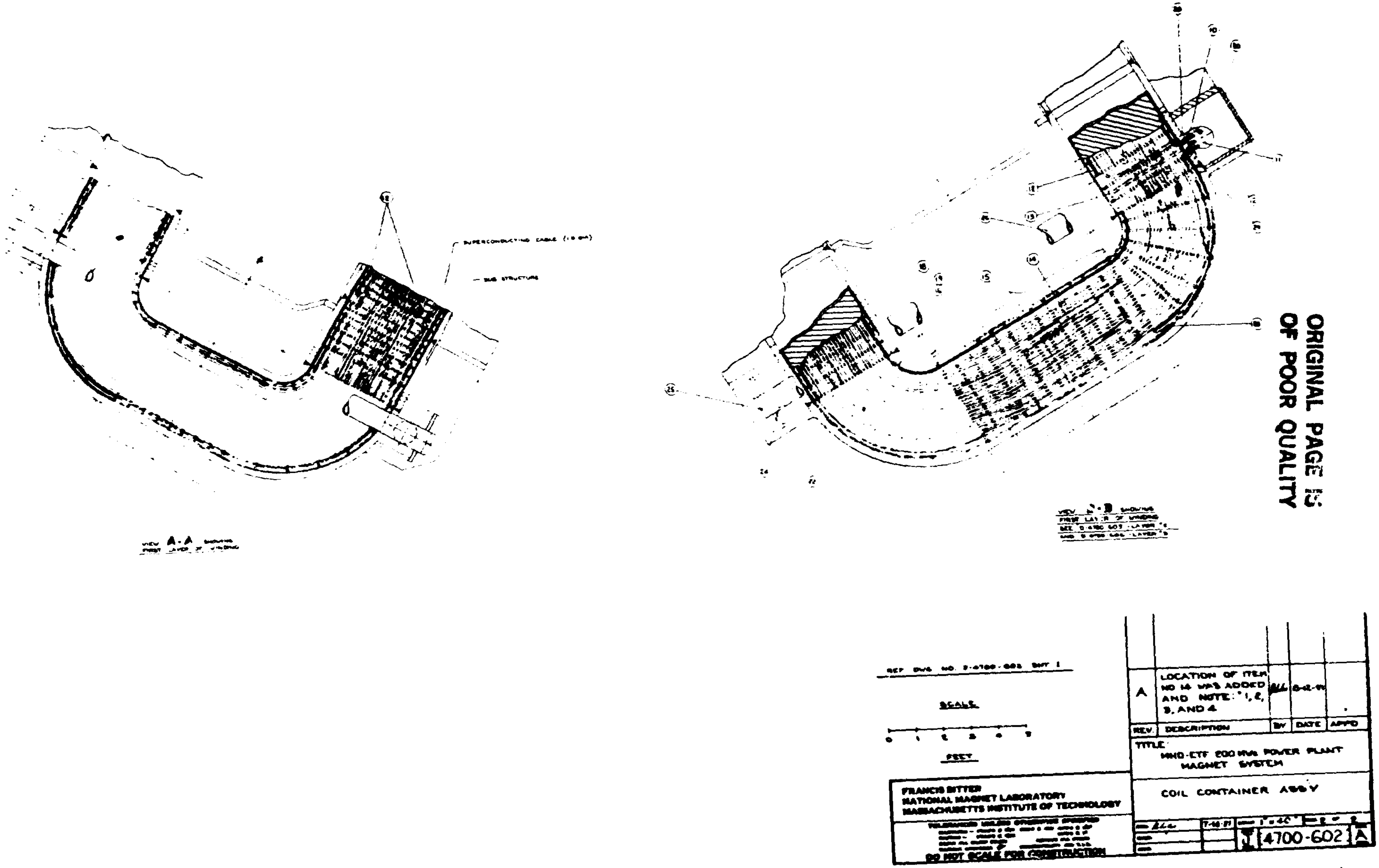

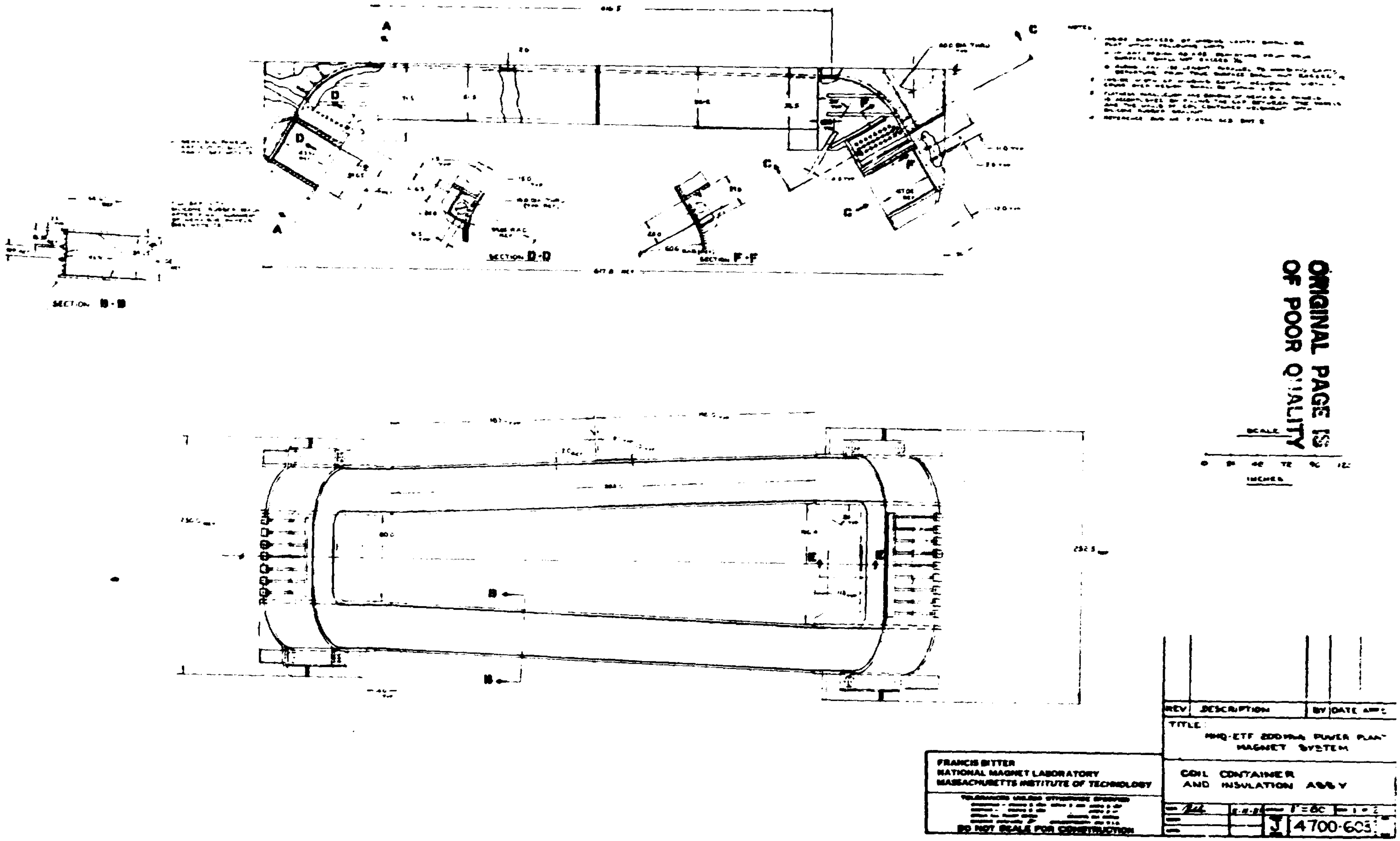
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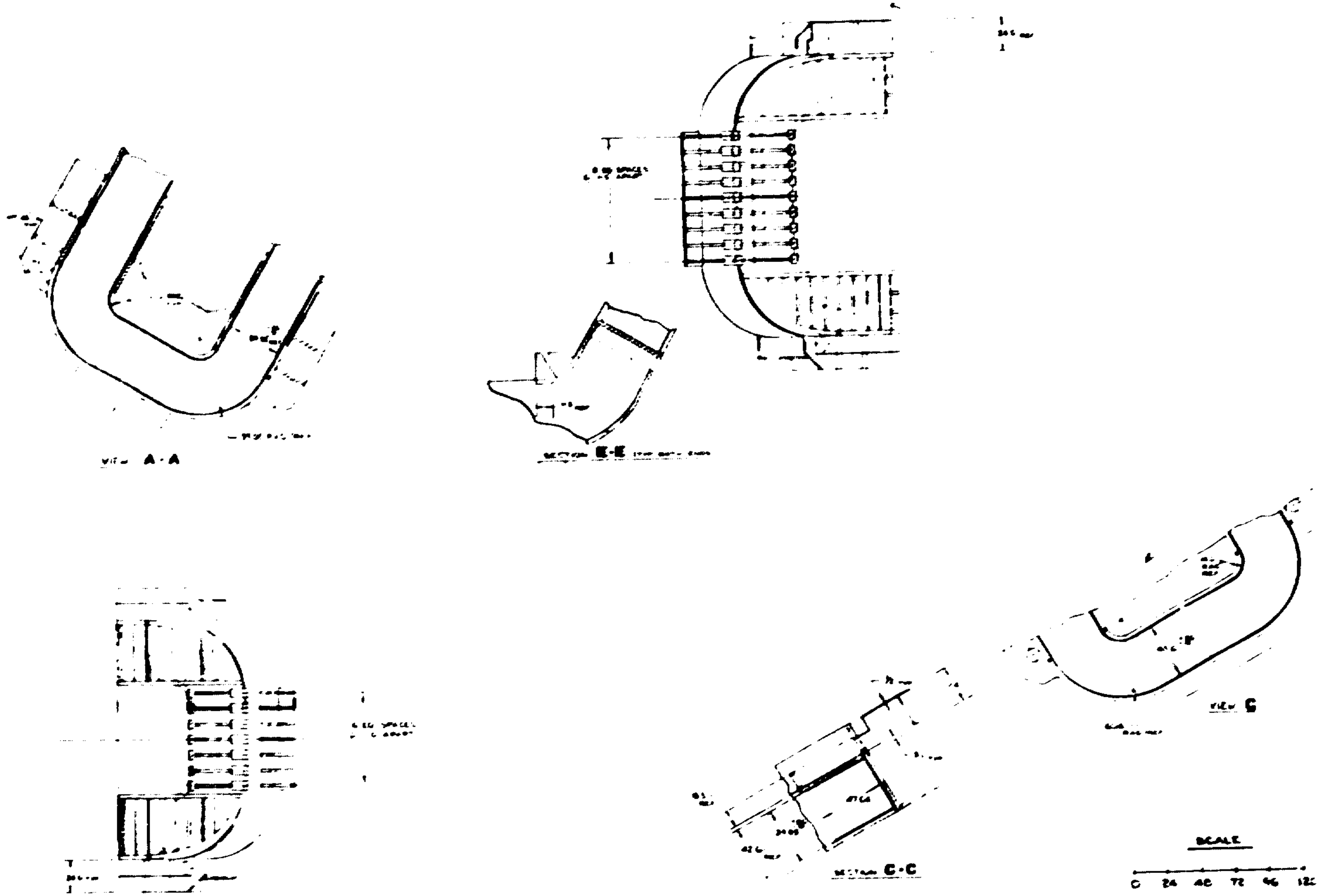

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COIL CONTAINER AND INSULATION ASS'Y

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J 4700-603

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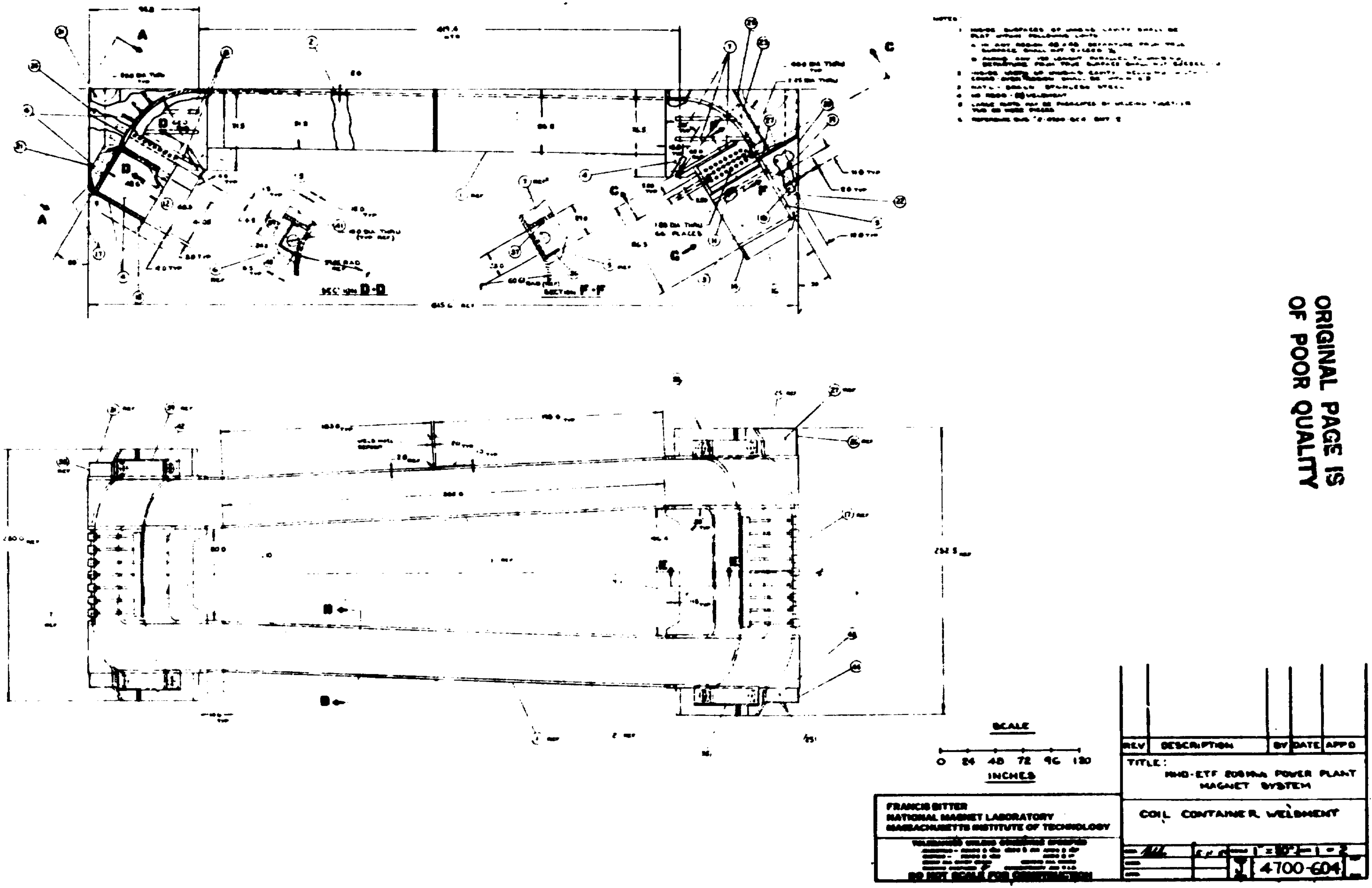

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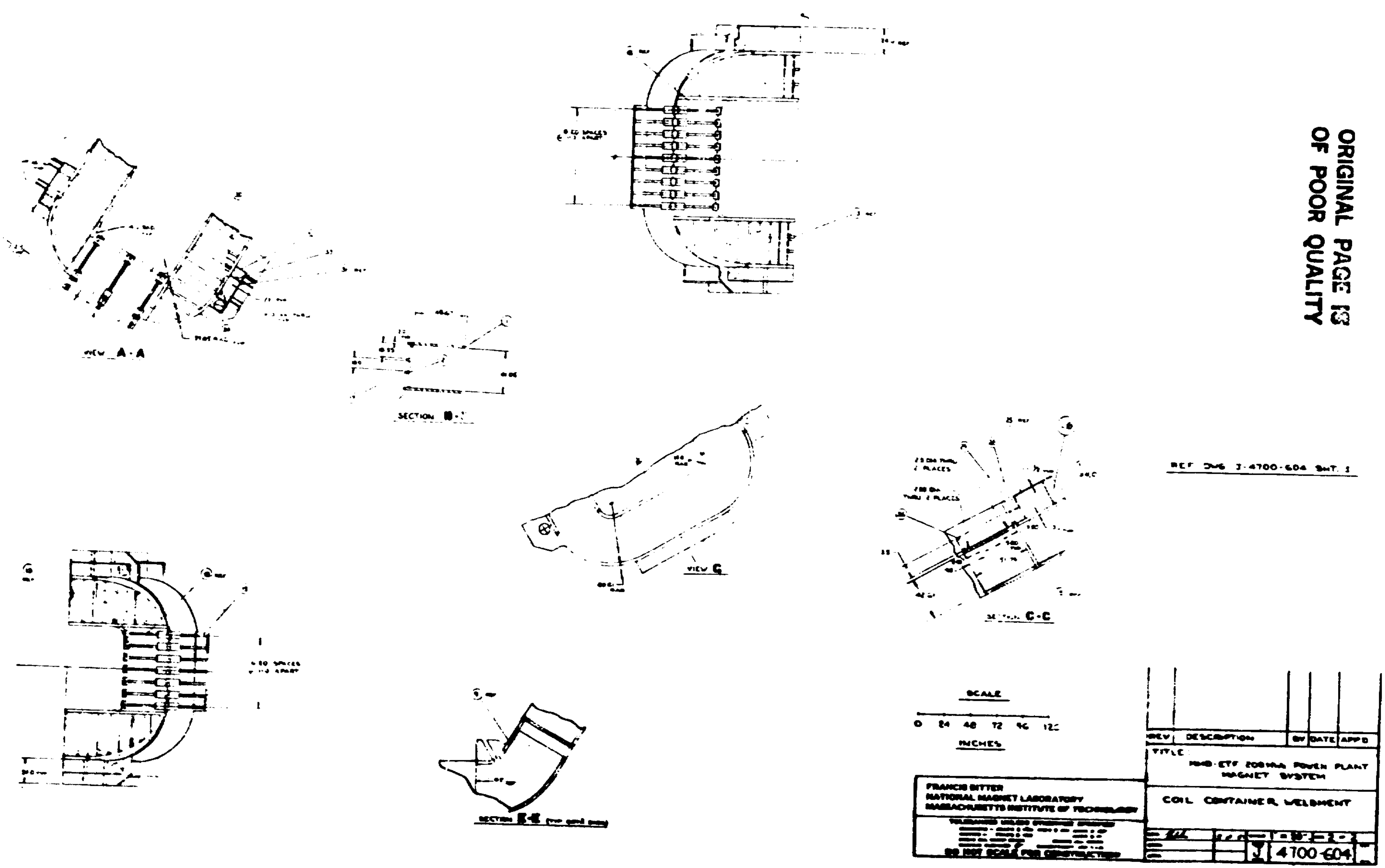

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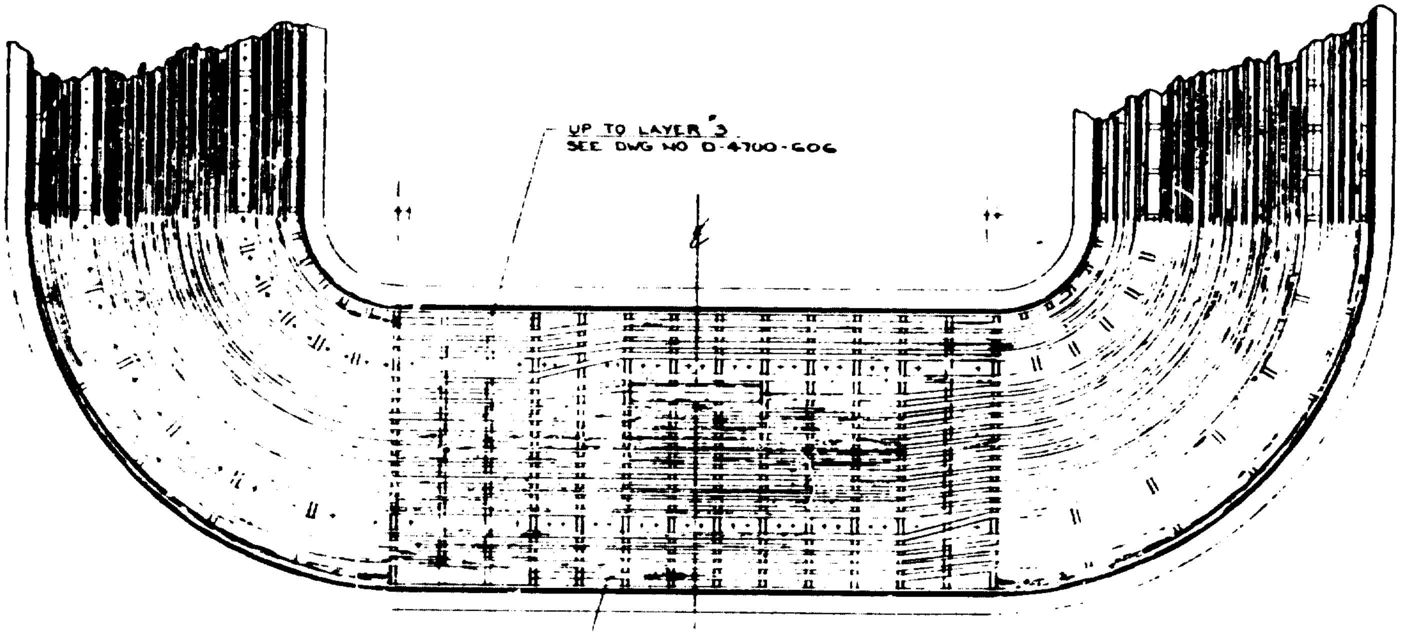

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MHD-ETF 200 MWe POWER PLANT
MAGNET SYSTEM

LAYER 2
WINDING DETAIL

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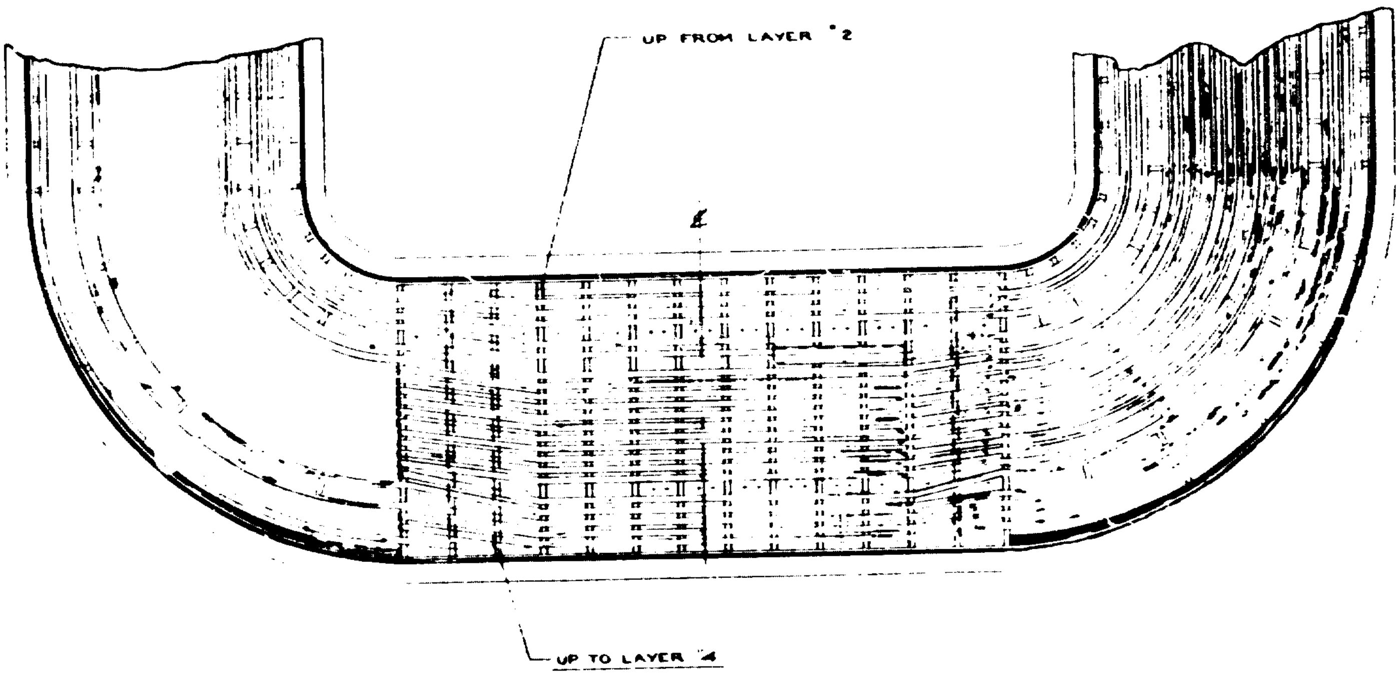

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LAYER #3 WINDING DETAIL

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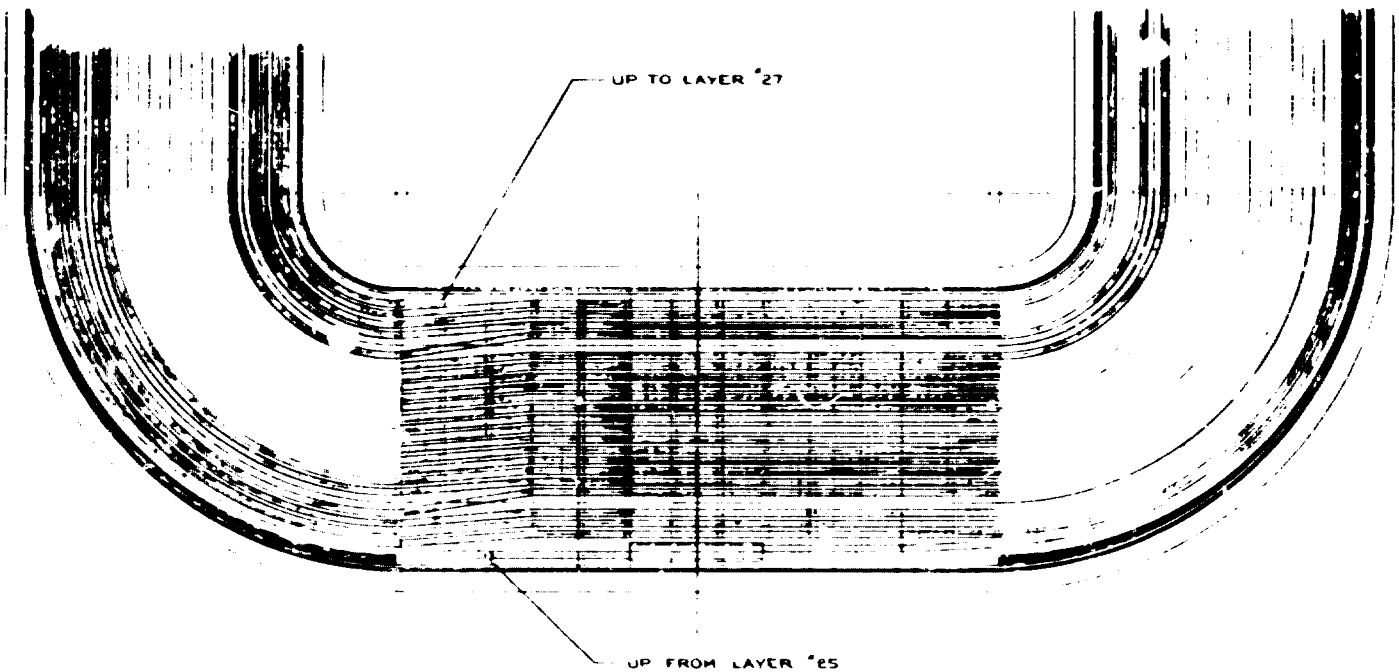

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LAYER #26
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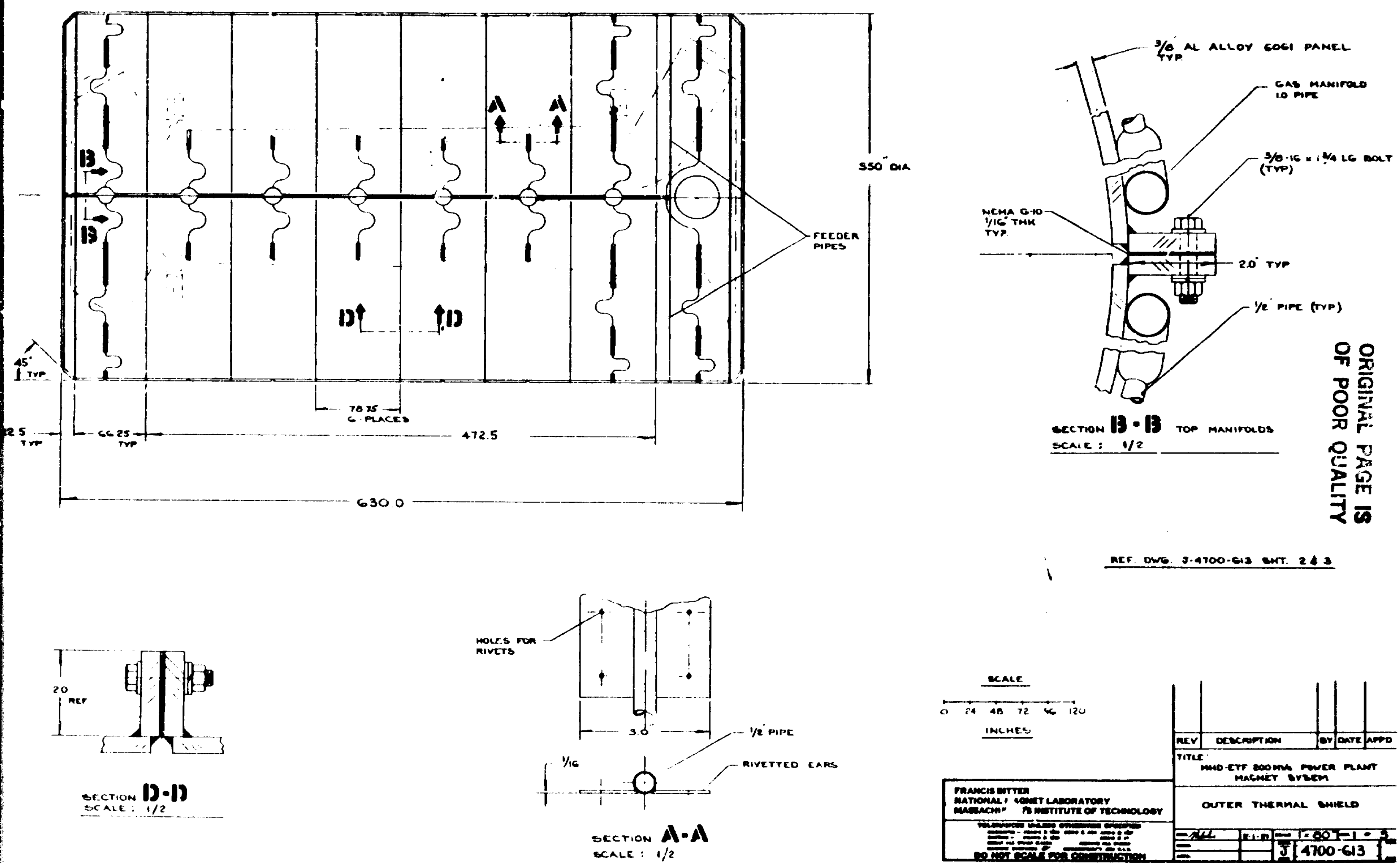
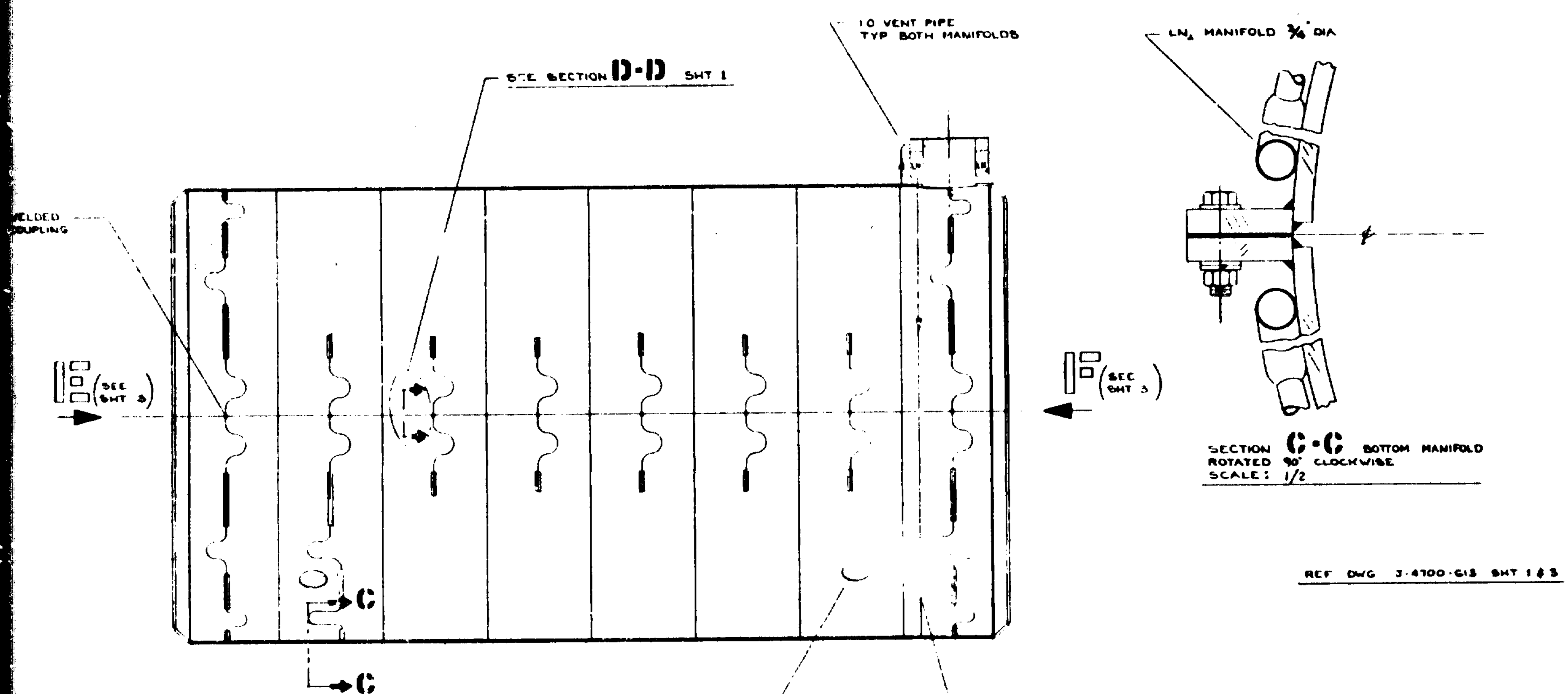
DO NOT SCALE FOR CONSTRUCTION

D 4700-607


550" DIA
FEEDER PIPES
78.75
6 PLACES
472.5
2.5 TYP
66.25 TYP
630.0
45° TYP
3/8" AL ALLOY 6061 PANEL TYP
GAS MANIFOLD 1.0 PIPE
3/8-16 x 1 3/4 LG BOLT (TYP)
NEMA G-10 1/16" THK TYP
2.0" TYP
1/2" PIPE (TYP)
SECTION B-B TOP MANIFOLDS
SCALE : 1/2
REF. DWG. J-4700-613 SHT. 2 & 3
20 REF
SECTION D-D
SCALE : 1/2
HOLES FOR RIVETS
3.0"
1/2" PIPE
1/16
RIVETTED EARS
SECTION A-A
SCALE : 1/2
SCALE
0 24 48 72 96 120
INCHES
REV
DESCRIPTION
BY
DATE
APPD
TITLE:
MHD-ETF 200 MWe POWER PLANT MAGNET SYSTEM
OUTER THERMAL SHIELD
FRANCIS BITTER NATIONAL MAGNET LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DO NOT SCALE FOR CONSTRUCTION
J
4700-613



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OF POOR QUALITY

REV	DESCRIPTION	BY	DATE	APPD

TITLE
MHD-ETF 200 MWe POWER PLANT
MAGNET SYSTEM

OUTER THERMAL SHIELD

FRANCIS BITTER
NATIONAL MAGNET LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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1" = 60' — 2 — 3
J 4700-613

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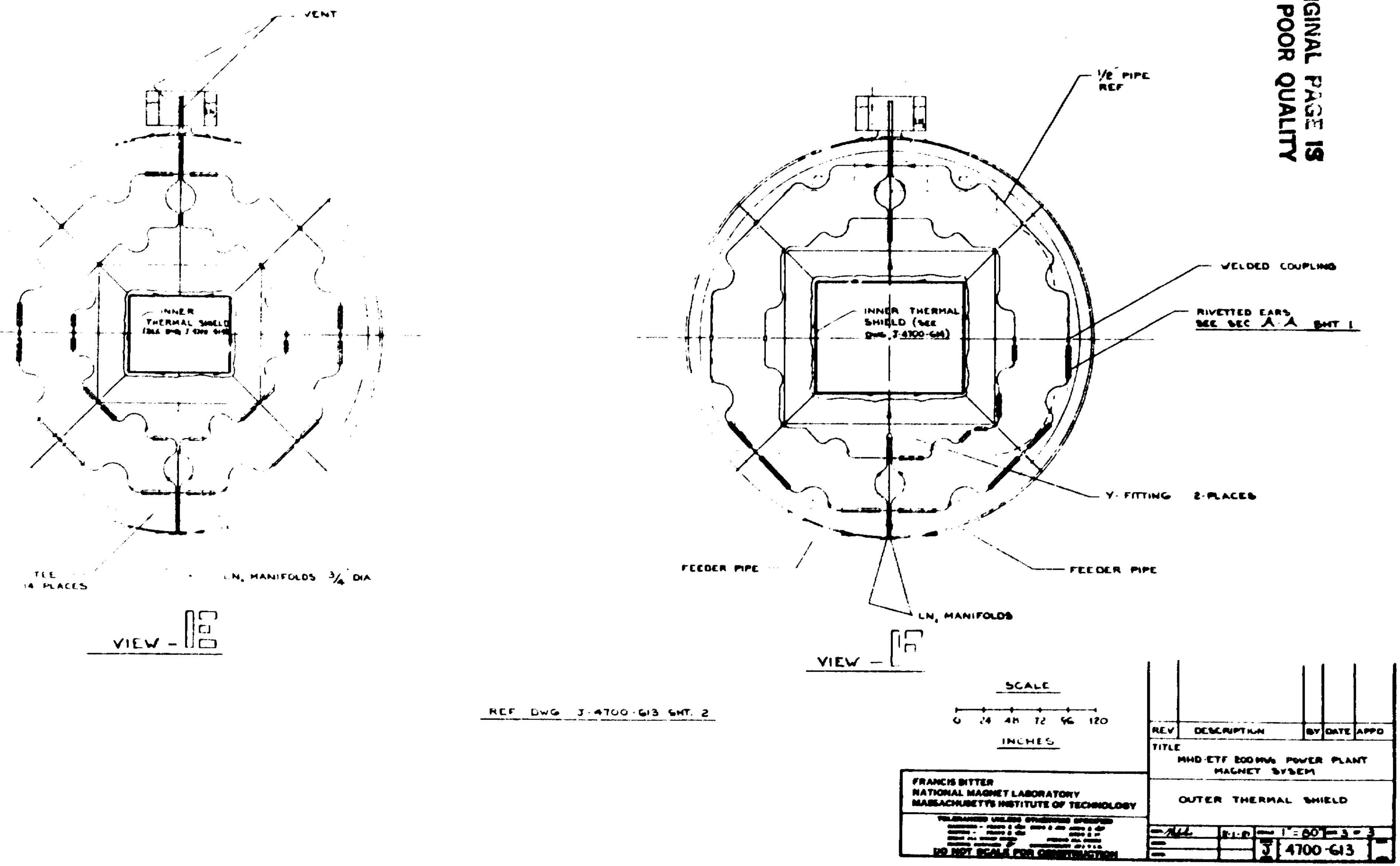

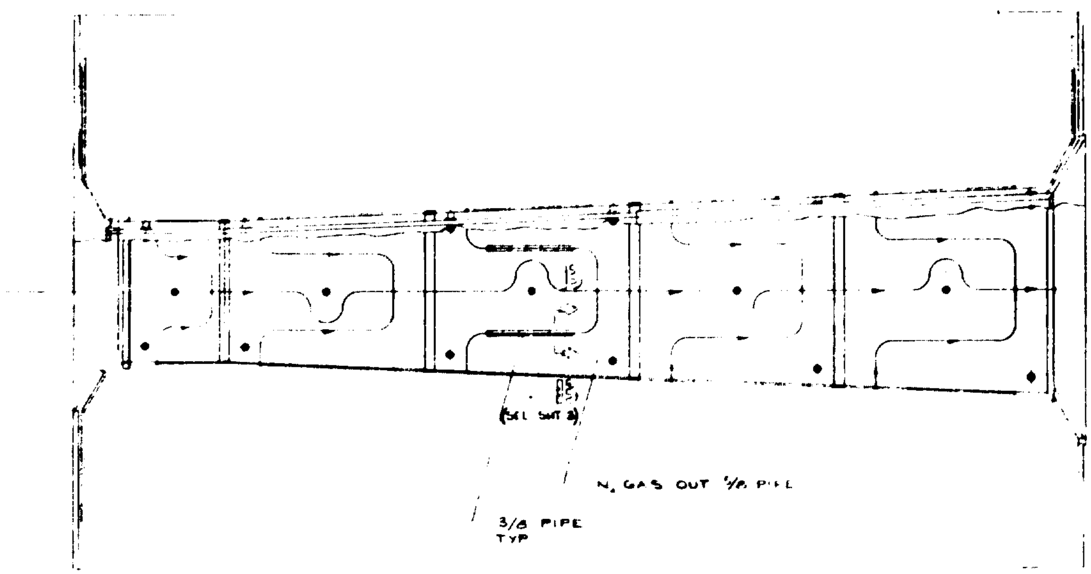
(SEE SHT 3)
N_2 GAS OUT 1/2 PIPE
3/8 PIPE
TYP
REF DWG J-4700-G14 SHT 2&3
SCALE
0 24 48 72 96 120
INCHES
REV
DESCRIPTION
BY
DATE
APPD
TITLE:
MHD ETF 200MW POWER PLANT
MAGNET SYSTEM
INNER THERMAL SHIELD
FRANCIS BITTER
NATIONAL MAGNET LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DO NOT SCALE FOR CONSTRUCTION
1" = 80"
J
4700-G14

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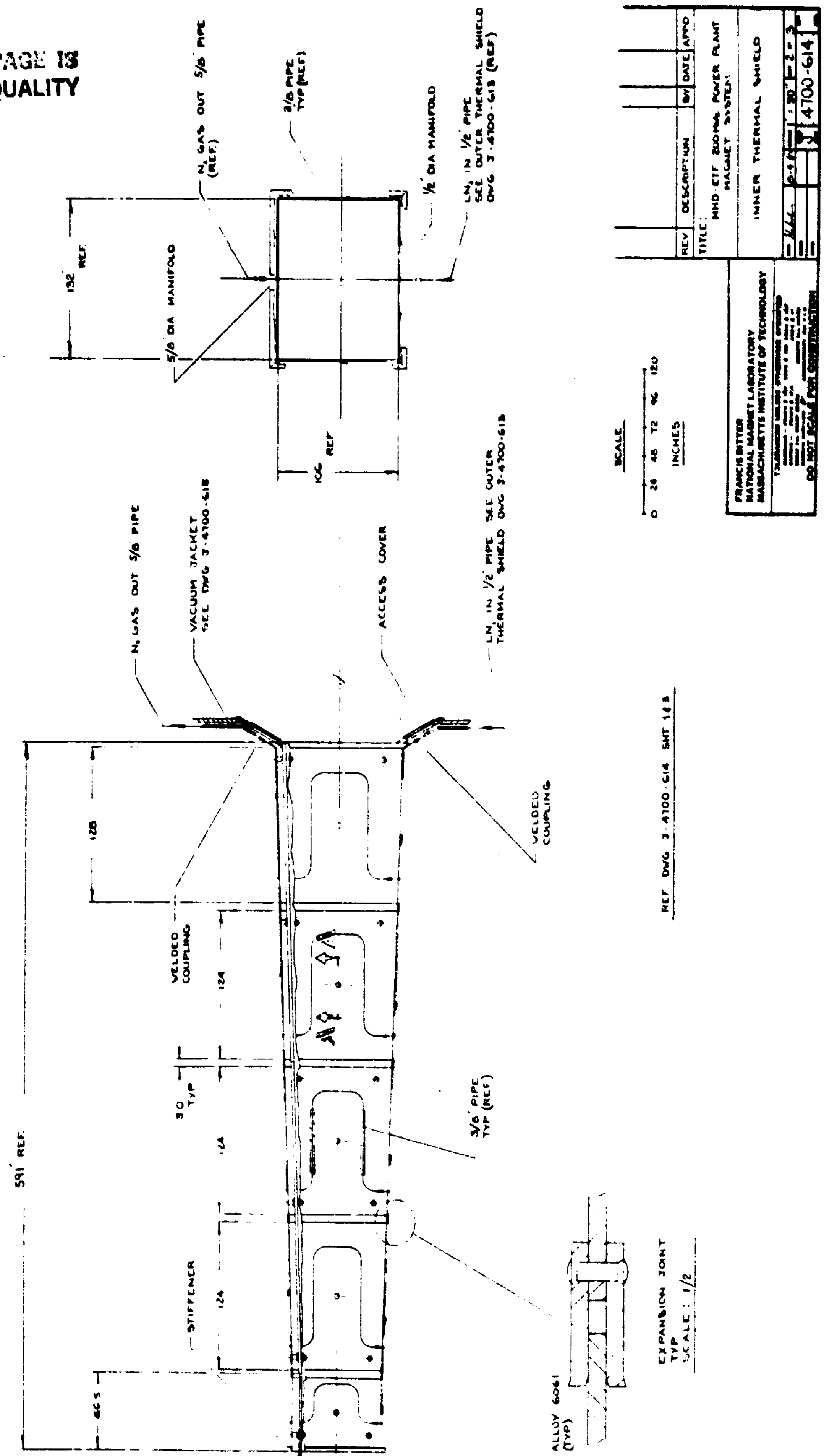
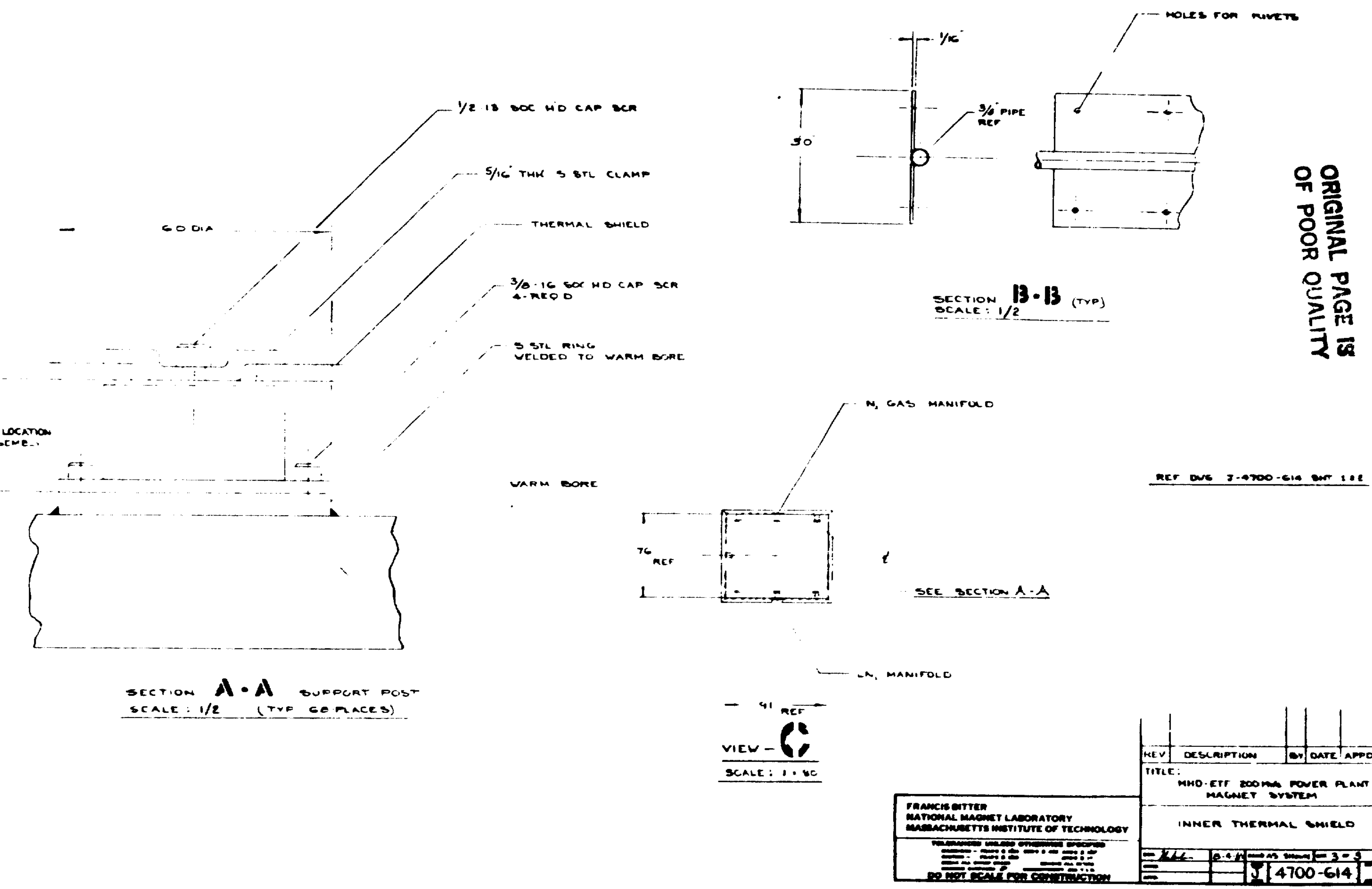
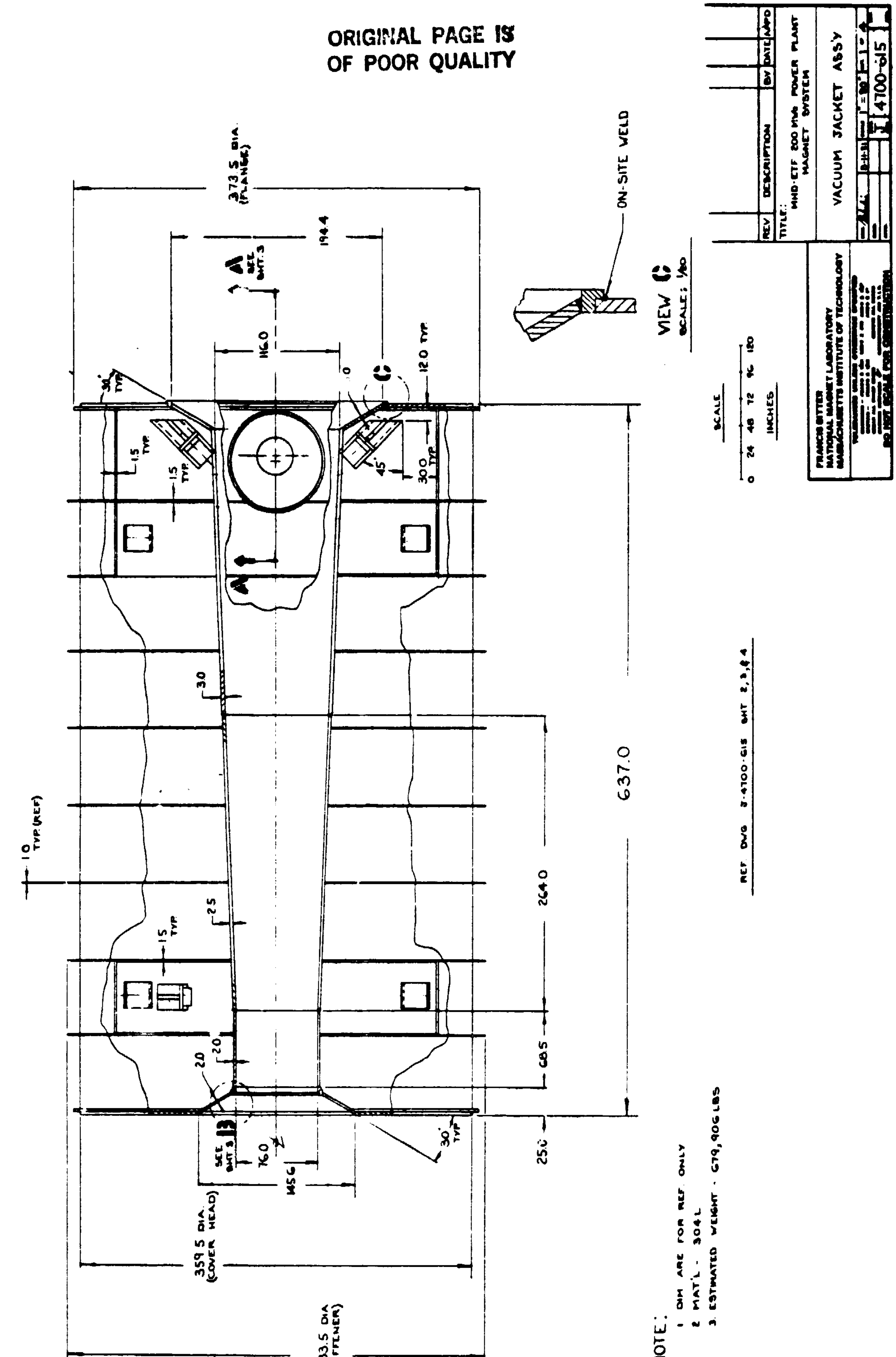
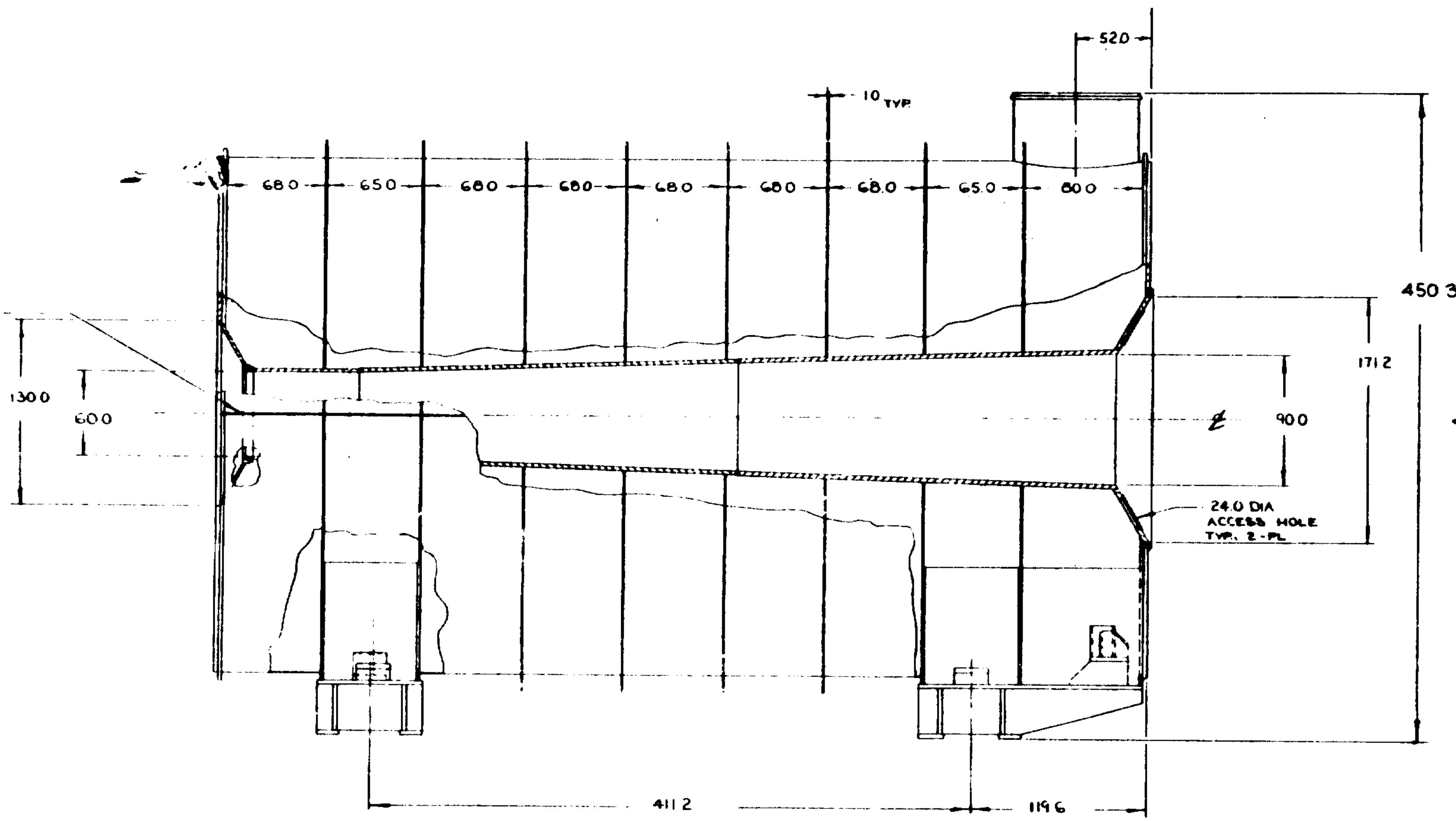




1/2-13 SOC HD CAP SCR
5/16" THK S STL CLAMP
THERMAL SHIELD
3/8-16 SOC HD CAP SCR
4-REQ'D
S STL RING
WELDED TO WARM BORE
60 DIA
WARM BORE
LOCATION
SECTION A-A SUPPORT POST
SCALE: 1/2 (TYP 68 PLACES)
1/16"
30"
3/4" PIPE
REF
HOLES FOR RIVETS
SECTION B-B (TYP)
SCALE: 1/2
N2 GAS MANIFOLD
76
REF
SEE SECTION A-A
LN2 MANIFOLD
91
REF
VIEW - C
REF DWG 3-4700-614 SHT 1&2
REV
DESCRIPTION
BY
DATE
APPD
TITLE:
MHD-ETF 200MW POWER PLANT
MAGNET SYSTEM
INNER THERMAL SHIELD
FRANCIS BITTER
NATIONAL MAGNET LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
TOLERANCES UNLESS OTHERWISE SPECIFIED
DO NOT SCALE FOR CONSTRUCTION
3 of 3
J 4700-614


373.5 DIA (FLANGE)
194.4
116.0
A SEE SHT. 3
12.0 TYP
30° TYP
1.5 TYP
1.5 TYP
45°
30.0 TYP
C
ON-SITE WELD
VIEW C SCALE: 1/30
3.0
637.0
264.0
10 TYP (REF)
25
1.5 TYP
2.0
2.0
68.5
25.0
30° TYP
B SEE SHT. 3
76.0
145.6
359.5 DIA (COVER HEAD)
SCALE
0 24 48 72 96 120
INCHES
REF DWG 3-4700-015 SHT 2, 3, & 4
REV
DESCRIPTION
BY
DATE
APPD
TITLE:
MHD-ETF 200 MWe POWER PLANT MAGNET SYSTEM
VACUUM JACKET ASS'Y
FRANCIS BITTER NATIONAL MAGNET LABORATORY MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DO NOT SCALE FOR CONSTRUCTION
4700-015
NOTE:
1. DIM ARE FOR REF ONLY
2. MAT'L - 304L
3. ESTIMATED WEIGHT - 679,906 LBS



REF. DWG. J 4700-615 SHT 1, 3, & 4

SCALE

0 24 48 72 96 120

INCHES

REV	DESCRIPTION	BY	DATE	APP'D

TITLE: MHD-ETF 200 MWe POWER PLANT MAGNET SYSTEM

VACUUM JACKET ASS'Y

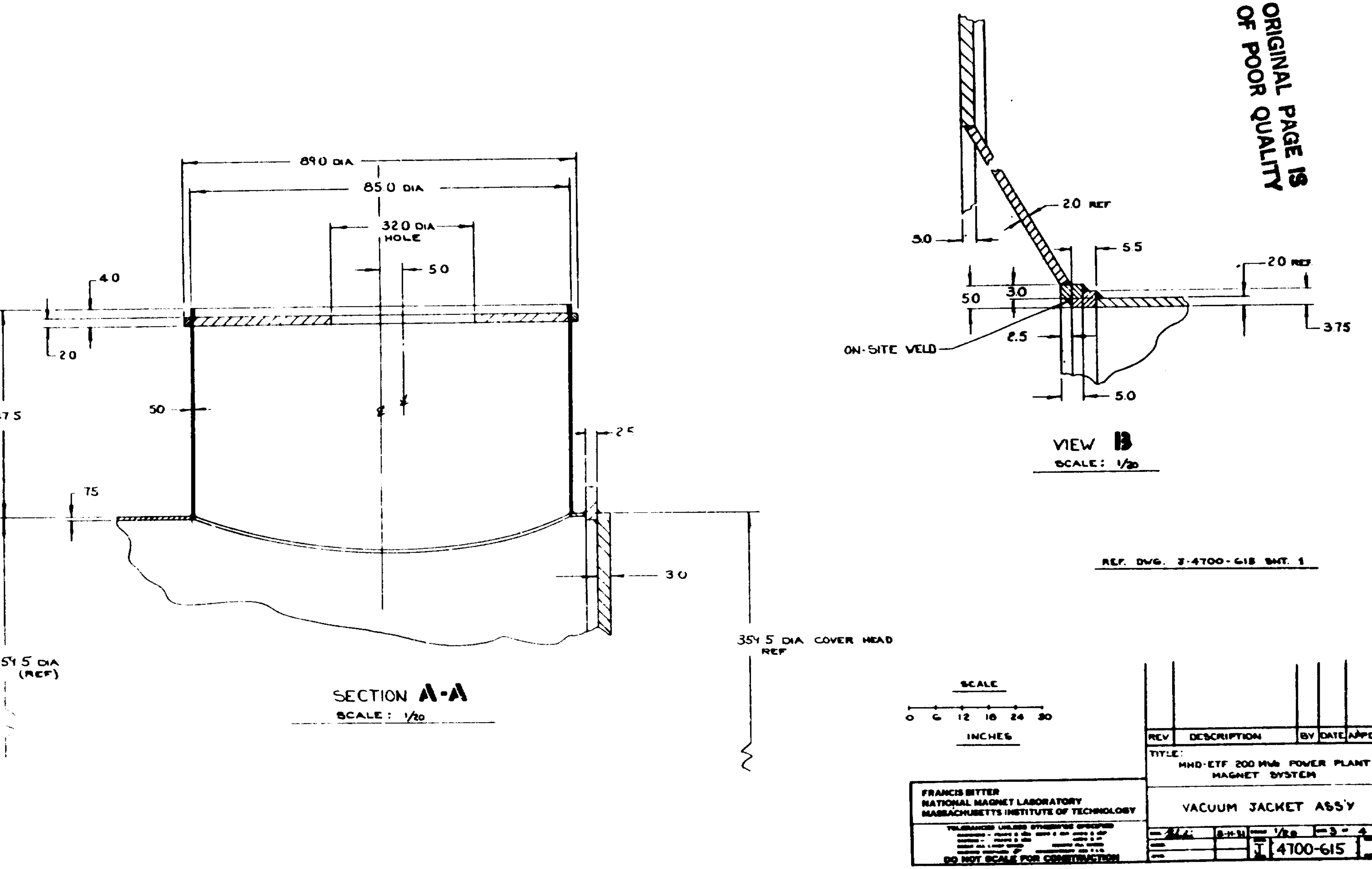
FRANCIS BITTER NATIONAL MAGNET LABORATORY MASSACHUSETTS INSTITUTE OF TECHNOLOGY

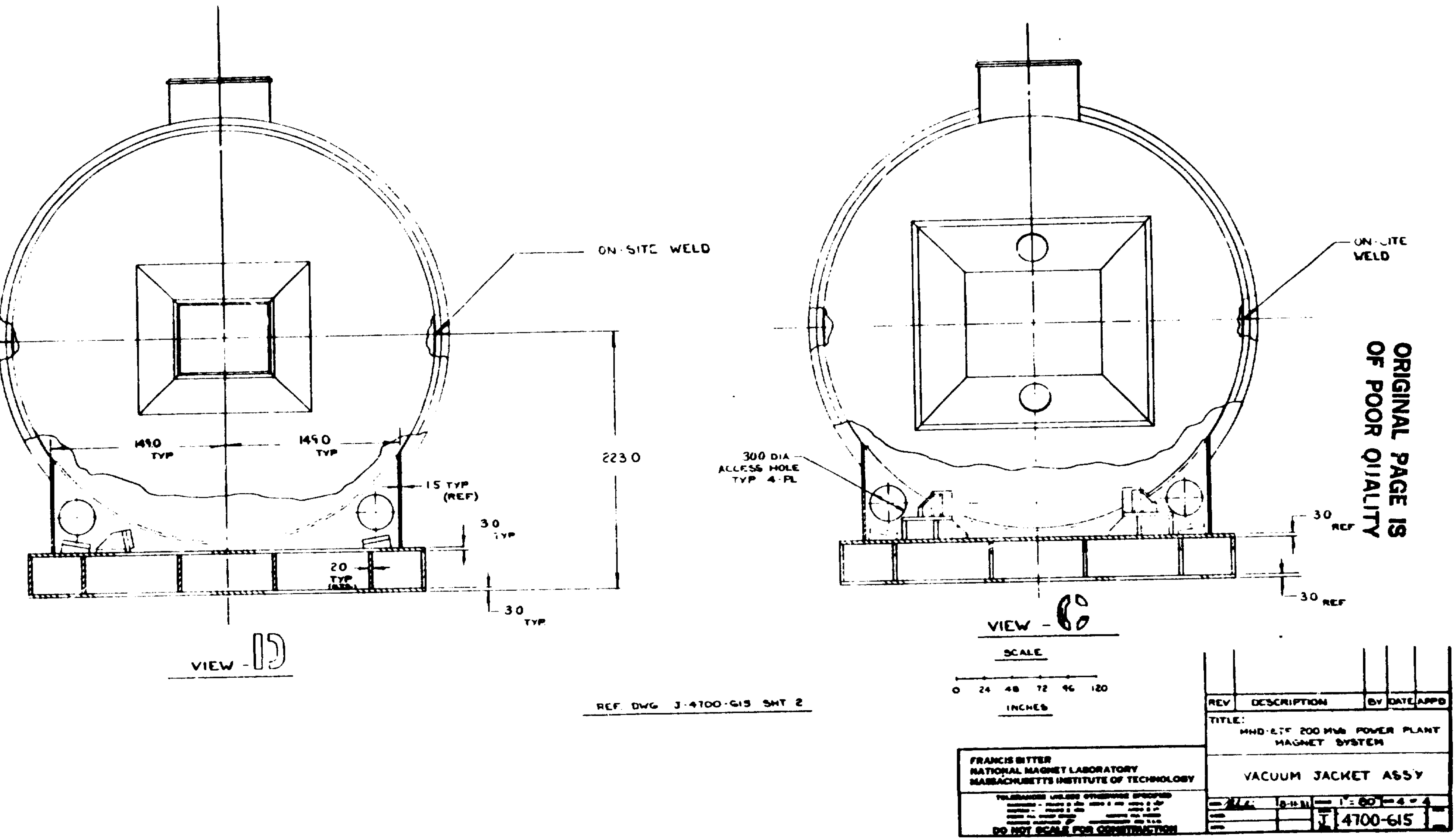
TOLERANCES UNLESS OTHERWISE SPECIFIED

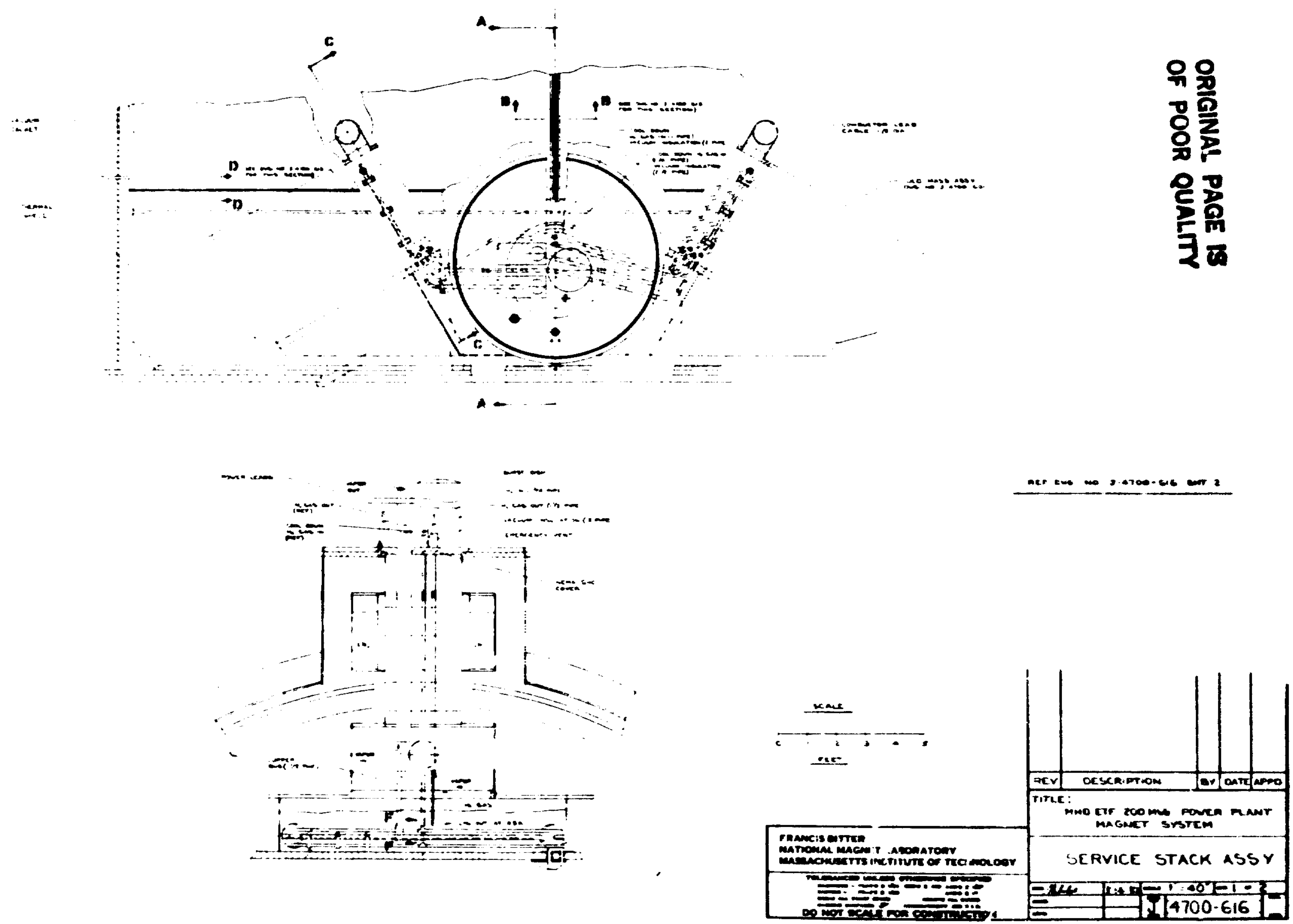
DO NOT SCALE FOR CONSTRUCTION

1" = 30' 2 of 4

J 4700-615


89.0 DIA
85.0 DIA
32.0 DIA
HOLE
4.0
5.0
2.0
50
.75
2.5
3.0
354.5 DIA COVER HEAD
REF
354.5 DIA
(REF)
SECTION A-A
SCALE: 1/20
2.0 REF
5.0
5.5
2.0 REF
5.0
3.0
3.75
2.5
ON-SITE WELD
5.0
VIEW B
SCALE: 1/20
REF. DWG. 3-4700-618 SHT. 1
SCALE
0 6 12 18 24 30
INCHES
REV
DESCRIPTION
BY
DATE
APPD
TITLE:
MHD-ETF 200 MWe POWER PLANT
MAGNET SYSTEM
VACUUM JACKET ASS'Y
FRANCIS BITTER
NATIONAL MAGNET LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DO NOT SCALE FOR CONSTRUCTION
1/20
4700-615


ON-SITE WELD
149.0 TYP
149.0 TYP
223.0
15 TYP (REF)
30 TYP
20 TYP (REF)
30 TYP
VIEW - D
REF DWG J-4700-615 SHT 2
ON-SITE WELD
300 DIA ACCESS HOLE TYP 4-PL
30 REF
30 REF
VIEW - C
SCALE
0 24 48 72 96 120
INCHES
ORIGINAL PAGE IS OF POOR QUALITY
REV
DESCRIPTION
BY
DATE
APPD
TITLE:
MHD-ETF 200 MWe POWER PLANT MAGNET SYSTEM
VACUUM JACKET ASSY
FRANCIS BITTER NATIONAL MAGNET LABORATORY MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DO NOT SCALE FOR CONSTRUCTION
1" = 80'
J
4700-615


A
B
C
D
REF DWG NO 2-4700-616 SHT 2
SCALE
FEET
REV
DESCRIPTION
BY
DATE
APPD
TITLE:
MHD ETF 200 MWe POWER PLANT
MAGNET SYSTEM
SERVICE STACK ASSY
FRANCIS BITTER
NATIONAL MAGNET LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DO NOT SCALE FOR CONSTRUCTION
1:40
4700-616

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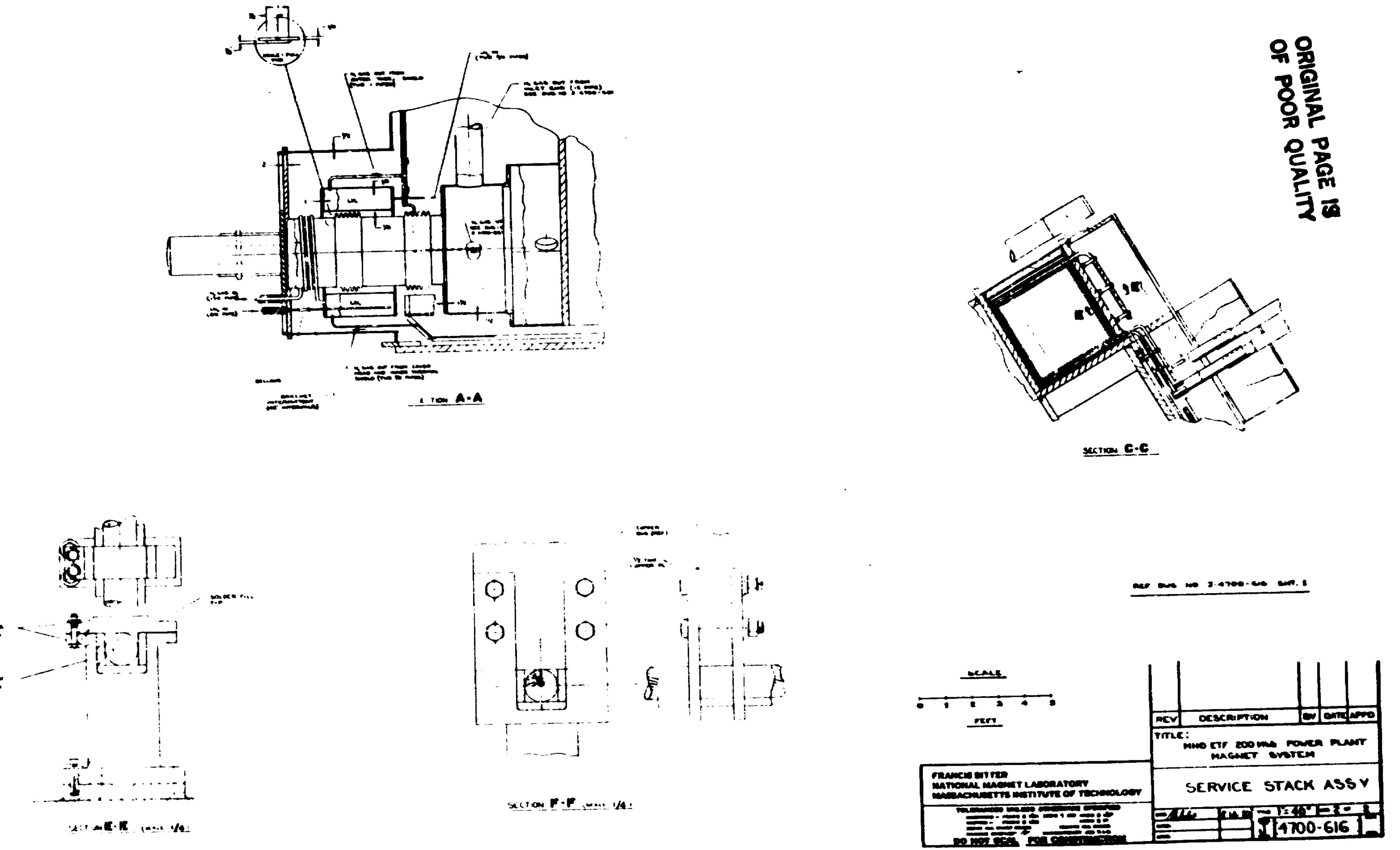

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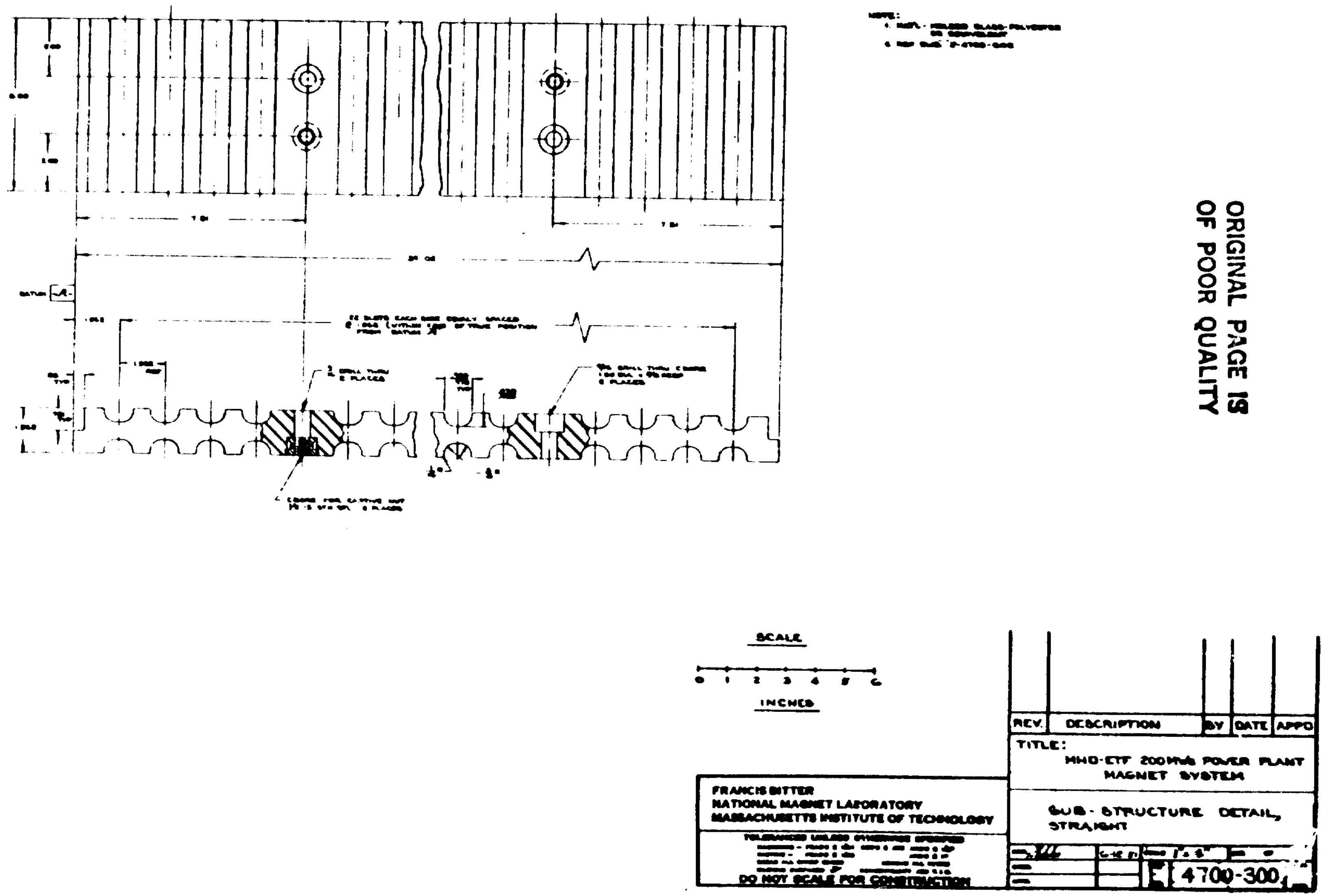

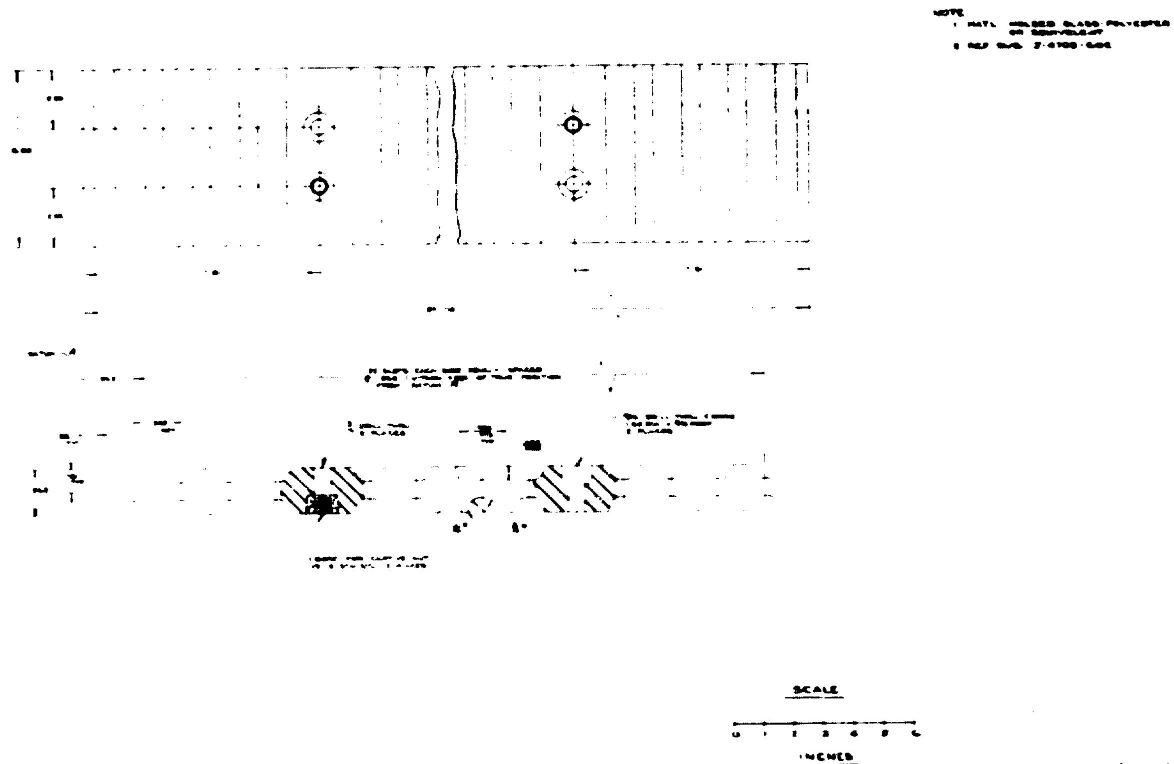

REV	DESCRIPTION	BY	DATE	APPD

TITLE:
MHD ETT 200MWe POWER PLANT
MAGNET SYSTEM

SUB-STRUCTURE DETAIL,
STRAIGHT

FRANCIS BITTER
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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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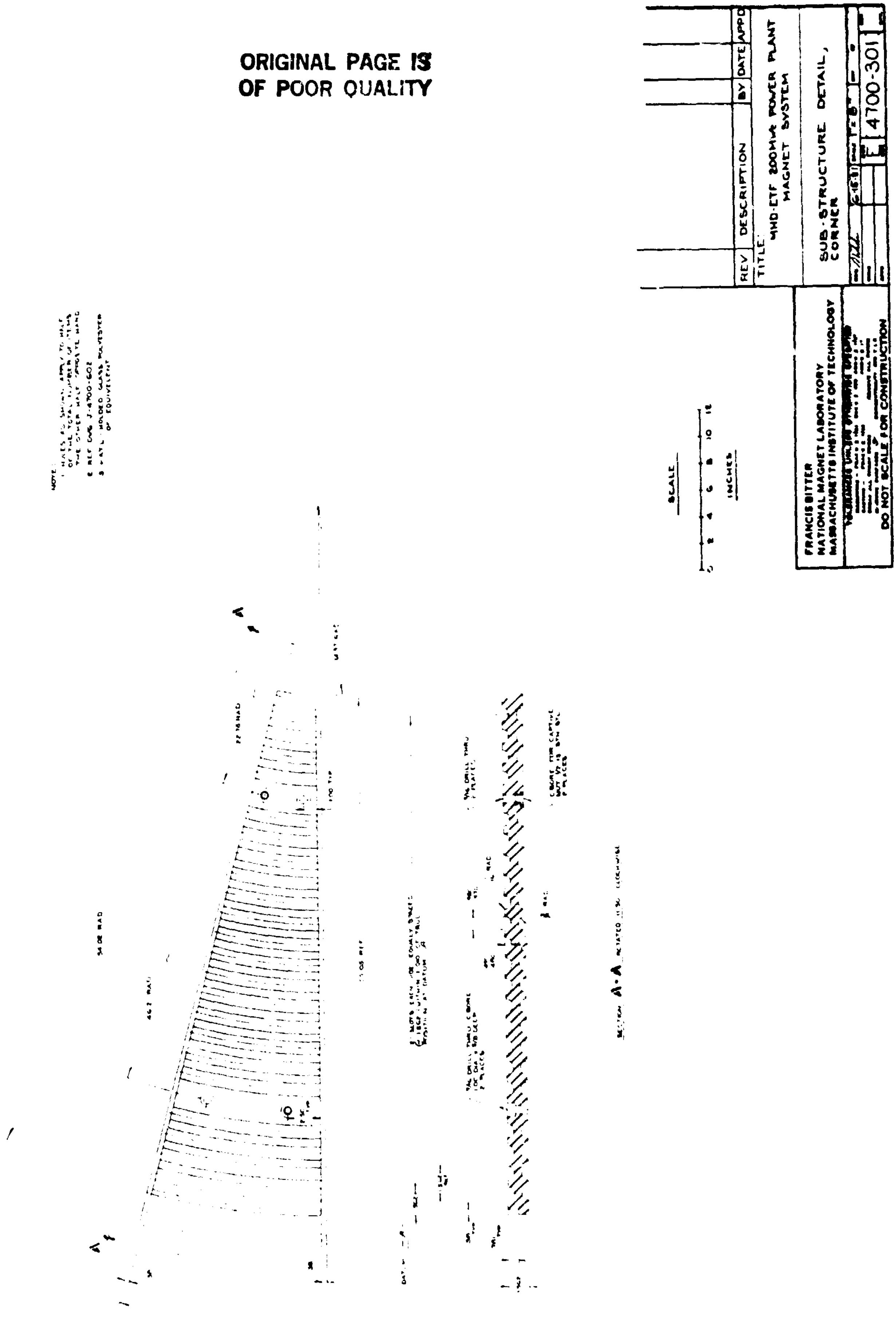
4700-300


REV
DESCRIPTION
BY
DATE
APPD
TITLE
MHD-ETF 200MWe POWER PLANT
MAGNET SYSTEM
SUB-STRUCTURE DETAIL,
CORNER
FRANCIS BITTER
NATIONAL MAGNET LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DO NOT SCALE FOR CONSTRUCTION
E
4700-301
SCALE
INCHES
0 2 4 6 8 10 12
SECTION A-A
A
A

ORIGINAL PAGE IS
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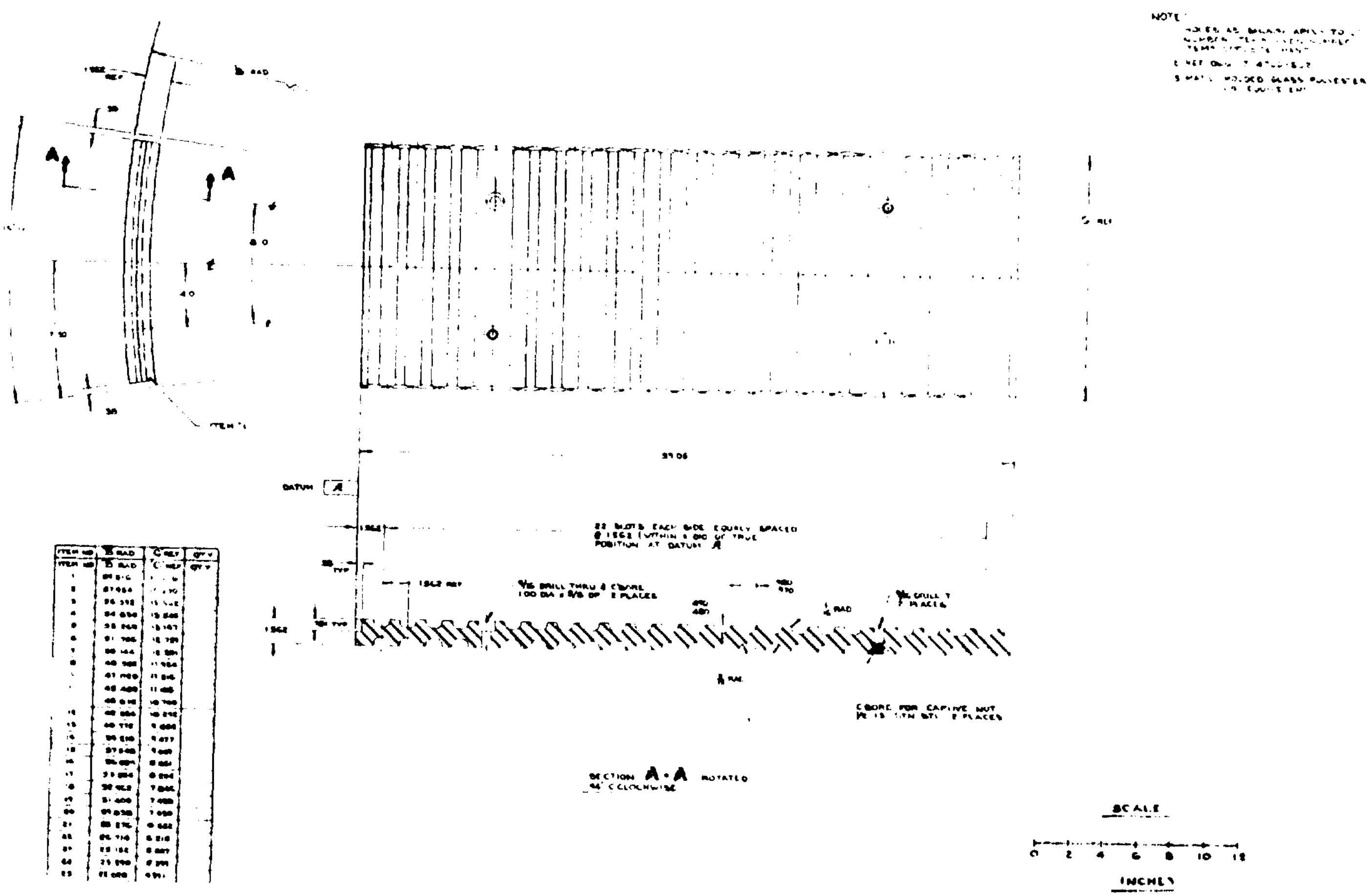

REV.	DESCRIPTION	BY	DATE	APPD

TITLE:
MHD-ETF 200 MWe POWER PLANT
MAGNET SYSTEM

SUB-STRUCTURE DETAIL
CURVED

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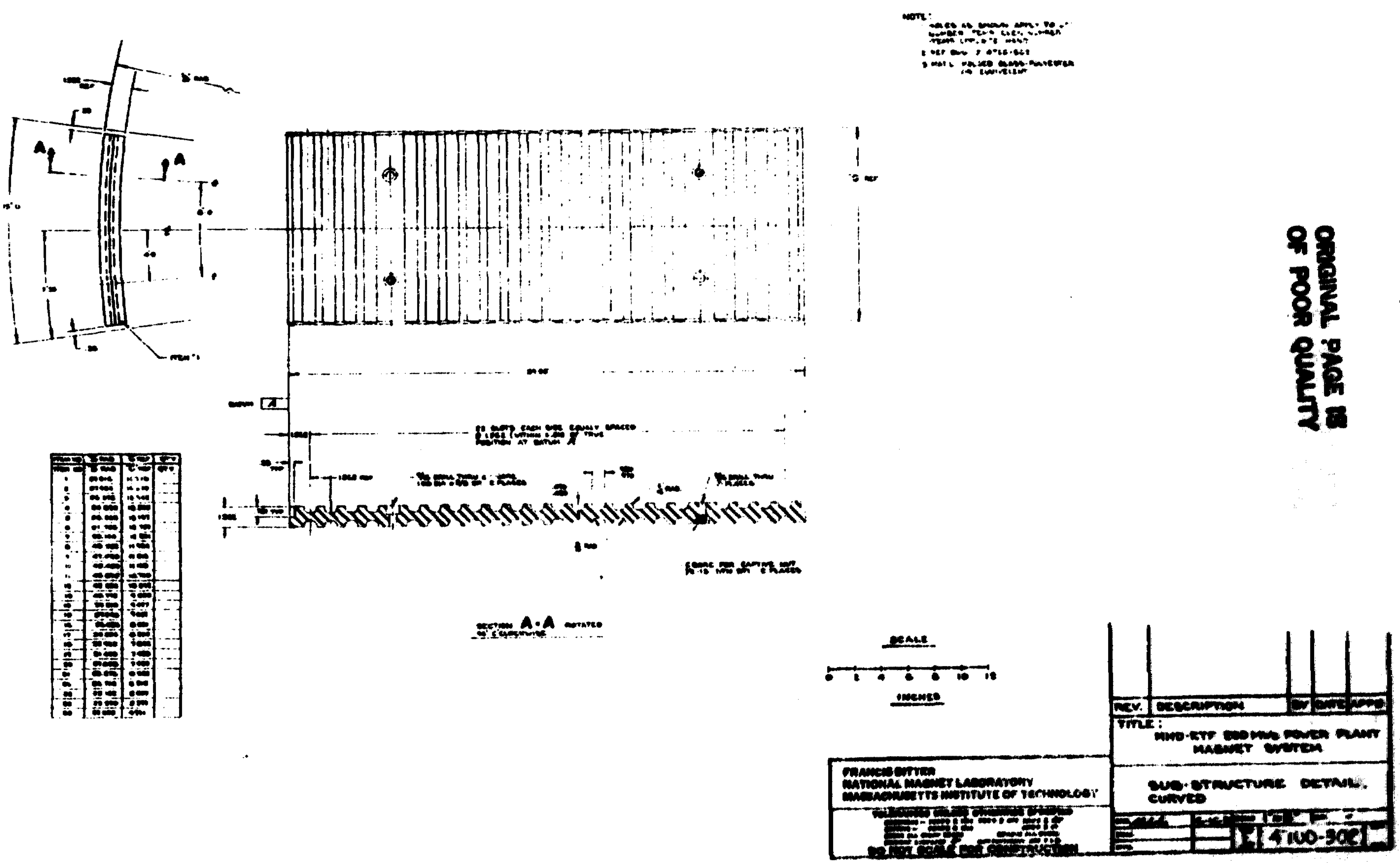
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

TOLERANCES UNLESS OTHERWISE SPECIFIED

DO NOT SCALE FOR CONSTRUCTION

E 4100-302


A
A
SECTION A-A ROTATED
SCALE
0 2 4 6 8 10 12
INCHES
FRANCIS BITTER
NATIONAL MAGNET LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DO NOT SCALE FOR CONSTRUCTION
REV.
DESCRIPTION
BY
DATE
APPD
TITLE :
MHD-ETF 500 MWe POWER PLANT
MAGNET SYSTEM
SUB-STRUCTURE DETAIL,
CURVED
4100-30C